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MONTHLY WEATHER REVIEW

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NOTICE OF CHANGE IN MONTHLY WEATHER REVIEW

The monthly climatological data tables carried in the Monthly Weather Review through December 1949 now appear in "Climatological Data, National Summary" (no price has yet been set). Paid subscribers to the Monthly Weather Review will receive both publications until their present subscriptions expire.

Although the Monthly Weather Review no longer publishes climatological data tables, it continues to survey the weather of the month. The survey consists of two monthly articles:

1. A discussion of the month's weather, including an interpretation of Charts I–XI in relation to the mean circulation patterns of the Northern Hemisphere.
2. A discussion of an outstanding weather situation of the month, including an analysis and interpretation of the meteorological features shown by synoptic weather charts.

In addition to reviewing the weather of the month, the Monthly Weather Review continues to publish contributions to meteorological science, particularly articles on synoptic and applied meteorology.

CORRECTION

The prices quoted for the "Climatological Data, National Summary" on page 325 of the December issue of the Monthly Weather Review are incorrect. No price has yet been set for the publication.

DEPARTMENT OF COMMERCE
CHARLES SAWYER, Secretary

WEATHER BUREAU
F. W. REICHELDERFER, Chief

MONTHLY WEATHER REVIEW

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VERIFICATION OF FORECASTS EXPRESSED IN TERMS OF PROBABILITY

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[Manuscript received February 10, 1950]

INTRODUCTION

Verification of weather forecasts has been a controversial subject for more than a half century. There are a number of reasons why this problem has been so perplexing to meteorologists and others but one of the most important difficulties seems to be in reaching an agreement on the specification of a scale of goodness for weather forecasts. Numerous systems have been proposed but one of the greatest arguments raised against forecast verification is that forecasts which may be the "best" according to the accepted system of arbitrary scores may not be the most useful forecasts. In attempting to resolve this difficulty the forecaster may often find himself in the position of choosing to ignore the verification system or to let it do the forecasting for him by "hedging" or "playing the system." This may lead the forecaster to forecast something other than what he thinks will occur, for it is often easier to analyze the effect of different possible forecasts on the verification score than it is to analyze the weather situation. It is generally agreed that this state of affairs is unsatisfactory, as one essential criterion for satisfactory verification is that the verification scheme should influence the forecaster in no undesirable way. Unfortunately, the criterion is difficult, if not impossible to satisfy, although some schemes will be much worse than others in this respect.

It is the purpose of this paper to discuss one situation where it appears to be possible to devise a verification scheme that cannot influence the forecaster in any undesirable way. This is the case when forecasts are expressed in terms of probability statements. The advantages of expressing the degree of assumed reliability of a forecast numerically have been discussed previously [1, 2, 3, 4] so that the purpose here will not be to emphasize the enhanced usefulness of such forecasts but rather to point out how some aspects of the verification problem are simplified or solved.

VERIFICATION FORMULA

Suppose that on each of n occasions an event can occur in only one of r possible classes or categories and on one such occasion, i, the forecast probabilities are f_{i1}, f_{i2}, . . . f_{ir}, that the event will occur in classes 1, 2, . . . r, respectively. The r classes are chosen to be mutually exclusive and exhaustive so that

$$\sum_{j=1}^{r} f_{ij}=1,\ i=1,2,3,\ldots n \tag{1}$$

A number of interesting observations can be made about a vertification score P defined by

$$P=\frac{1}{n}\sum_{j=1}^{r}\sum_{i=1}^{n}(f_{ij}-E_{ij})^2 \tag{2}$$

where E_{ij} takes the value 1 or 0 according to whether the event occurred in class j or not. Before discussing this score in detail it will be instuctive to consider an illustrative example. Table 1 shows 10 actual forecasts ($n=10$) of rain or no-rain ($r=2$) in which a probability or confidence statement (f_{ij}) was made for each forecast. In the table, in accordance with the definition of E_{ij}, unity is placed in the rain column and zero in the no-rain column if rain occurs; and if the event is no-rain, unity is placed in the no-rain column and zero in the rain

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column. According to formula (2) the score P for these forecasts is

$$P=\frac{1}{10}(0.7^2+0.1^2+0.2^2+\ldots+0.1^2)=0.19$$

From consideration of this example or of formula (2), it is obvious that the score P has a minimum value of zero for perfect forecasting and a maximum value of 2 for the worst possible forecasting. Perfect forecasting is defined as correctly forecasting the event to occur with a probability of unity or 100 percent confidence. The worst possible forecast is defined as stating a probability of unity or certainty for an event that did not materialize (and also, of course, stating a probability of zero for the event that did materialize).

It is also easy to show that if $p_1, p_2, \ldots p_r$, are the relative frequencies that the event occurred in classes $1, 2, \ldots r$, then the minimum score that can be obtained by forecasting the same thing on every occasion is when

$$f_{ij}=p_j, \qquad i=1, 2, \ldots n \tag{3}$$

This will minimize the score P for constant values of $f_{1j}=f_{2j}=\ldots f_{nj}$ and the mean value of the score will be

$$P'=1-\sum_{j=1}^{r} p_j^2 \tag{4}$$

In the example given here (table 1) there are two classes, rain or no-rain, so $r=2$. It rained 3 out of 10 times so if the forecaster had no skill in differentiating one occasion from another, thus making the same forecast each time, he should put down 0.3 for the probability of rain and 0.7 for the probability of no-rain in order to get the best score. Of course in actual practice he doesn't know in advance the relative frequencies $p_1, p_2, \ldots p_r$ so he would ordinarily use the best estimates of the p_j based on climatological studies. The important point is, however, that if he has some skill in forecasting an average departure from the climatological probabilities he should make use of it. Thus, in the example given, a forecast of 0.3 probability for rain on every occasion would give a score

$$P'=1-(0.3^2+0.7^2)=0.42$$

If for these same 10 forecasts a climatological probability of say 0.2 for rain had been used on every occasion the corresponding score is 0.44. Thus the forecaster receives credit for recognizing or forecasting a departure from the normal conditions through the period even though he may not be able to distinguish one occasion from another within the period.

TABLE 1.—*Example of forecasts stated in terms of probability*

Occasion i	Rain		No rain	
	Forecast probability f_{i1}	Observed E_{i1}	Forecast probability f_{i2}	Observed E_{i2}
1	0.7	0	0.3	1
2	.9	1	.1	0
3	.8	1	.2	0
4	.4	1	.6	0
5	.2	0	.8	1
6	0	0	1.0	1
7	0	0	1.0	1
8	0	0	1.0	1
9	0	0	1.0	1
10	.1	0	.9	1

In addition to encouraging the forecaster to minimize his score P by getting the forecasts exactly right and stating a probability of unity, he is encouraged to state unbiased estimates of the probability of each event when he cannot forecast perfectly. A little experience with the use of score P will soon convince him that he is fooling nobody but himself if he thinks he can beat the verification system by putting down only zeros and unities when his forecasting skill does not justify such statements of extreme confidence. And in the complete absence of any forecasting skill he is encouraged to predict the climatological probabilities instead of categorically forecasting the most frequent class on every occasion.

COMPARISON OF FORECAST AND OBSERVED PROBABILITIES

When a series of forecasts has been made using probability statements a study can also be made to determine whether the forecast probabilities are related to the relative frequency of the events' occurrence. An example of this type of comparison is shown in table 2 (based on a more extended series of such forecasts), which suggests a relationship between the forecast and observed probabilities but indicates that the forecaster should modify or adjust his scale to improve the forecasts. However, knowledge of a good relationship between forecast and observed probabilities is not sufficient to indicate how useful the forecasts are, for it is also necessary to know the frequency with which forecasts are made in the various categories. In general, the most useful forecasts are those which fall into the extreme classes shown in table 2. The score P depends on both the frequency distribution of the forecast probability statements and the correlation between the forecast and observed probabilities. In other words, in order for P to become smaller the correlation must increase and the proportion of forecasts in the extreme classes must increase.

TABLE 2.—*Verification of a series of 85 forecasts expressed in terms of the probability of rain*

Forecast probability of rain	Observed proportion of rain cases	Forecast probability of rain	Observed proportion of rain cases
0.00–0.19	0.07	0.60–0.79	0.40
0.20–0.39	.10	0.80–1.00	.50
0.40–0.59	.29		

CONCLUSIONS

During the past several months the score P has been used in the verification of some experimental precipitation forecasts for 6-hour periods made by members of the Short Range Forecast Development Section of the Weather Bureau. Although initially there was some criticism of this scoring method, most of it seemed to be a result of lack of understanding of the method or due to the disillusionment of finding so little ability to call for precipitation with much certainty or confidence. However, a few questions have been raised that indicate further study is needed regarding this particular scoring method and it is hoped that this paper will stimulate others to investigate this phase of the verification problem.

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WORLD'S GREATEST OBSERVED POINT RAINFALLS

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[Manuscript received December 15, 1949]

The accompanying figure 1 and table 1 present the most recent values of the depths and durations of the world's greatest observed point rainfalls. Since previous publication of similar data[1] several record rainfalls have occurred and many other records have been found. The most recent record is the 12-inch amount in 42 minutes at Holt, Mo., on June 22, 1947.

Some records recently found are those for Cherrapunji, India, in 1931 and the 2-day value for Funkiko, Formosa. A survey of the 1931 daily rainfall records for Cherrapunji, India, reveals that the 7- and 8-day accumulations are greater than those for like durations in 1876. The 15-day total in June–July 1931 is slightly more than half the record monthly total for July 1861 for which daily amounts are not available. The records for Funkiko, Formosa, show the greatest 2-day amount, as well as the greatest 3-day amount, replacing Cherrapunji for the 2-day record.

Some additional record amounts, which give support to the greatest observed amounts, are listed in table 1 but are not plotted on figure 1. These are marked with an asterisk.

Acknowledgement is made to J. T. Walser for assistance in obtaining the Cherrapunji records. C. S. Gladden drafted the chart.

[1] MONTHLY WEATHER REVIEW, December 1941, p. 357.

TABLE 1.—*World's greatest observed point rainfalls*

Duration	Depth (inches)	Station	Date	Reference
1 min	0.65	Opid's Camp, Calif.	Apr. 5, 1926	1
5 min	2.48	Porto Bello, Panama	Nov. 29, 1911	2
8 min	4.96	Füssen, Bavaria	May 25, 1920	3
14 min	3.95	Galveston, Tex.	June 4, 1871	2
15 min	7.80	Plumb Point, Jamaica	May 12, 1916	4
20 min	8.10	Curtea-de-Argès, Roumania	July 7, 1889	2
40 min	9.25	Guinea, Va.	Aug. 24, 1906	5
42 min	12.00	Holt, Mo.	June 22, 1947	6
1 hr	10.00	Catskill, N. Y.	July 26, 1819	7
1 hr, 20 min	11.50	Campo, Calif.	Aug. 21, 1891	8
2 hr, 10 min	19.00	Rockport, W. Va.	July 18, 1889	9
2 hr, 45 min	22.00	D'Hanis, Tex. (17 miles NNW).	May 31, 1935	10
3 hr	16.00	Concord, Pa.	Aug. 5, 1843	11
4 hr	23.00	Bassetere, St. Kitts, West Indies	Jan. 12, 1880	2
4 hr, 30 min	30.8+	Smethport, Pa.	July 18, 1942	12
12 hr	26.58	Baguio, Philippine Islands	July 15, 1911	13
15 hr	34.50	Smethport, Pa.	July 17–18, 1942	12
18 hr	36.40	Thrall, Tex.	Sept. 9, 1921	14
24 hr	45.99	Baguio, Philippine Islands	July 14–15, 1911	13
Do	40.80	Cherrapunji, India	June 14, 1876	15
Do	*40.71	Funkiko, Formosa	Aug. 31, 1911	16
Do	*40.10	Jowai, India	Sept. 11, 1877	17
39 hr	62.39	Baguio, Philippine Islands	July 14–16, 1911	13
2 days	65.79	Funkiko, Formosa	July 19–20, 1913	16
Do	*63.64	Cherrapunji, India	June 14–15, 1876	15
Do	*61.21	do	June 26–27, 1931	15
Do	*57.50	Silver Hill Plantation, Jamaica	Nov. 6–7, 1909	4
2 days, 15 hr	79.12	Baguio, Philippine Islands	July 14–17, 1911	13
3 days	81.54	Funkiko, Formosa	July 18–20, 1913	16
Do	*80.52	Cherrapunji, India	June 25–27, 1931	15
Do	*79.00	do	June 12–14, 1876	15
Do	*78.50	Silver Hill Plantation, Jamaica	Nov. 5–7, 1909	4
3 days, 15 hr	87.01	Baguio, Philippine Islands	July 14–18, 1911	13
4 days	101.84	Cherrapunji, India	June 12–15, 1876	15
Do	*96.50	Silver Hill Plantation, Jamaica	Nov. 5–8, 1909	4
Do	*94.28	Cherrapunji, India	June 24–27, 1931	15
5 days	150.—	do	August 1841	18
Do	114.50	Silver Hill Plantation, Jamaica	Nov. 5–9, 1909	4
Do	*114.14	Cherrapunji, India	June 12–16, 1876	15
Do	*107.17	do	June 24–28, 1931	15
6 days	122.50	Silver Hill Plantation, Jamaica	Nov. 5–10, 1909	4
Do	*119.37	Cherrapunji, India	June 11–16, 1876	15
Do	*116.35	do	June 24–29, 1931	15
7 days	131.15	do	June 24–30, 1931	15
Do	*129.00	Silver Hill Plantation, Jamaica	Nov. 4–10, 1909	4
Do	*126.69	Cherrapunji, India	June 10–16, 1876	15
8 days	135.05	do	June 24–July 1, 1931	15
Do	*135.00	Silver Hill Plantation, Jamaica	Nov. 4–11, 1909	4
Do	*133.39	Cherrapunji, India	June 9–16, 1876	15
15 days	188.88	do	June 24–July 8, 1931	15
31 days	366.14	do	July 1861	19
2 mo	502.63	do	June–July 1861	19
3 mo	644.44	do	May–July 1861	19
4 mo	737.70	do	Apr.–July 1861	19
5 mo	803.62	do	Apr.–Aug. 1861	19
6 mo	884.03	do	Apr.–Sept. 1861	19
11 mo	905.12	do	Jan.–Nov. 1861	19
1 yr	1,041.78	do	Aug. 1860–July 1861	19
2 yr	1,605.05	do	1860 and 1861	19

*Not plotted on chart.

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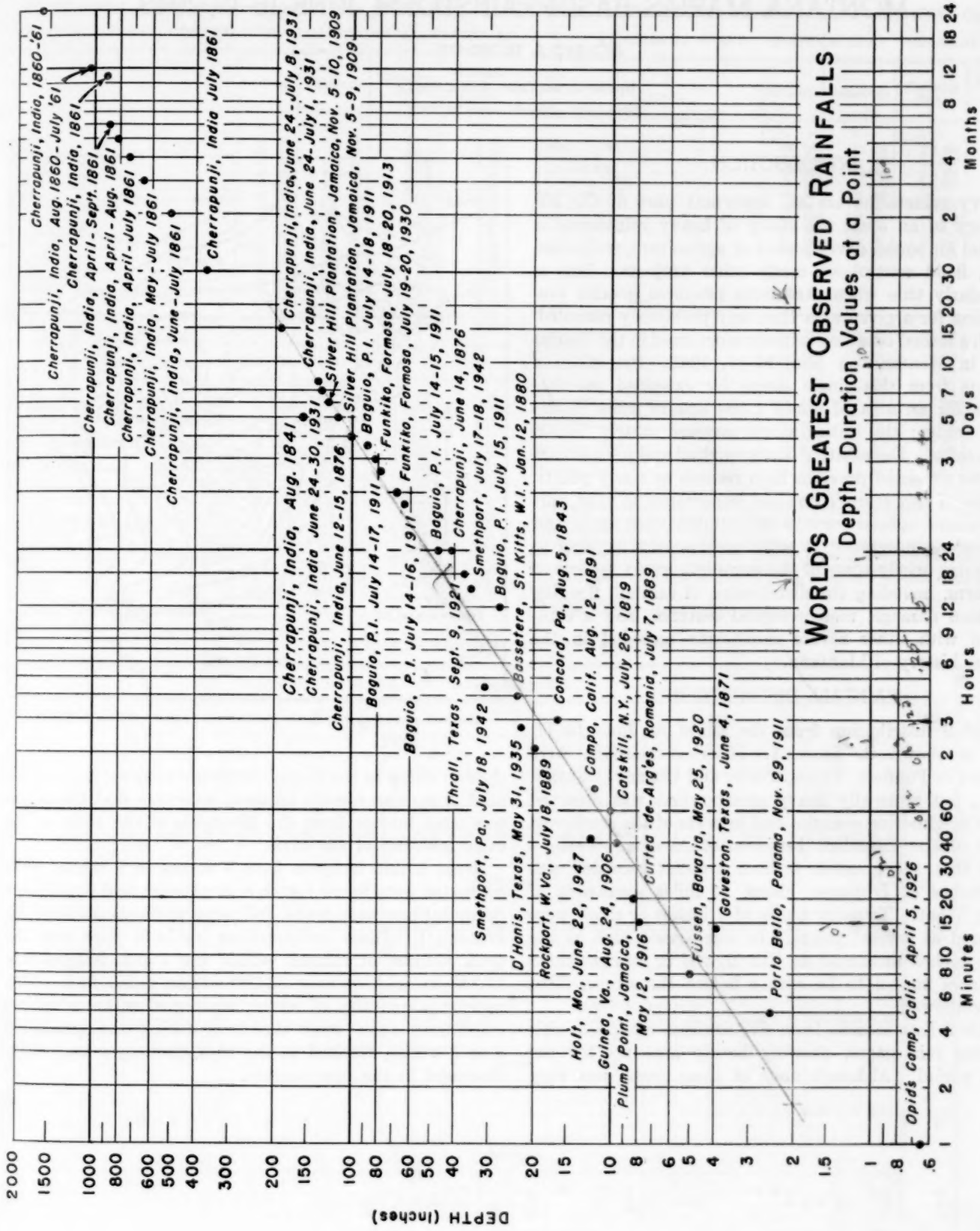
WORLD'S GREATEST OBSERVED RAINFALLS
Depth–Duration Values at a Point
DEPTH (Inches)
DURATION
Minutes
Hours
Days
Months
Cherrapunji, India, 1860-'61
Cherrapunji, India, Aug. 1860-July '61
Cherrapunji, India, April-Sept. 1861
Cherrapunji, India, April-Aug. 1861
Cherrapunji, India, April-July 1861
Cherrapunji, India, May-July 1861
Cherrapunji, India, June-July 1861
Cherrapunji, India July 1861
Cherrapunji, India, Aug. 1841
Cherrapunji, India June 24-30, 1931
Cherrapunji, India, June 24-July 8, 1931
Cherrapunji, India, June 24-July 1, 1931
Cherrapunji, India, June 12-15, 1876
Silver Hill Plantation, Jamaica, Nov. 5-10, 1909
Silver Hill Plantation, Jamaica, Nov. 5-9, 1909
Baguio, P.I. July 14-17, 1911
Baguio, P.I. July 14-18, 1911
Baguio, P.I. July 14-16, 1911
Funkito, Formosa, July 18-20, 1913
Funkito, Formosa, July 19-20, 1930
Baguio, P.I. July 14-15, 1911
Thrall, Texas, Sept. 9, 1921
Cherrapunji, June 14, 1876
Smethport, Pa., July 18, 1942
Smethport, July 17-18, 1942
O'Hanis, Texas, May 31, 1935
Baguio, P.I. July 15, 1911
Rockport, W. Va., July 18, 1889
Bassetere, St. Kitts, W.I., Jan. 12, 1880
Holt, Mo., June 22, 1947
Concord, Pa., Aug. 5, 1843
Guinea, Va., Aug. 24, 1906
Campo, Calif. Aug. 12, 1891
Plumb Point, Jamaica,
Catskill, N.Y., July 26, 1819
May 12, 1916
Curtea-de-Arges, Romania, July 7, 1889
Fussen, Bavaria, May 25, 1920
Galveston, Texas, June 4, 1871
Porto Bello, Panama, Nov. 29, 1911
Opid's Camp, Calif. April 5, 1926

FIGURE 1.

MONTANA MARIAS BASIN RAINSTORM, JUNE 16–17, 1948

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[Manuscript received January 26, 1949]

INTRODUCTION

Heavy rainstorms are an important part of the climatology of an area; the study of heavy rainstorms is essential for sound development of agriculture, irrigation, power, flood control, or many other projects. This is particularly true when the storm produces greater precipitation for a given area than any previously recorded.

Such a record-breaking rainstorm occurred in the Marias Basin in Montana on June 16–17, 1948. Precipitation amounts from this single storm far exceeded previous records for an area of about 1,000 square miles in the storm center; the entire storm covered nearly 10,000 square miles. Devastating floods resulted and peak stream flows far exceeded previous high records at many points. Because of this storm's unusual importance to that part of Montana, special surveys and studies were made and others are in progress. It is the purpose of this paper to summarize briefly some of the more important aspects of the storm, including the distribution of rainfall, flooding and flood damage, meteorological features, and a comparison with other severe rainstorms recorded in the weather history of Montana.

RAINFALL DISTRIBUTION

Rainfall distribution from the storm of June 16–17, 1948, is shown in figure 1. Heaviest rainfalls were recorded in Pondera, Teton, Toole, and Glacier Counties, Mont., but unusually heavy precipitation was reported also in neighboring counties and in parts of the southwest corner of the Canadian Province of Alberta. Table 1 shows that the greatest 48-hour amount recorded was 9.10 inches at Dupuyer, about 14 miles southwest of Valier, Mont. Two-day totals of 7 inches or more were measured at several points. In some cases such as the 7.00+ inches measured at Ethridge ½ S, straight-sided containers known to be empty before the storm, filled and overflowed.

Table 2 lists records from five stations equipped with weighing rain gages, showing hourly amounts for the storm period. Although none of these gages was very close to either of the storm's apparent centers, the records tend to confirm reports by most observers that the storm was most intense from the afternoon of the 16th to the early morning of the 17th.

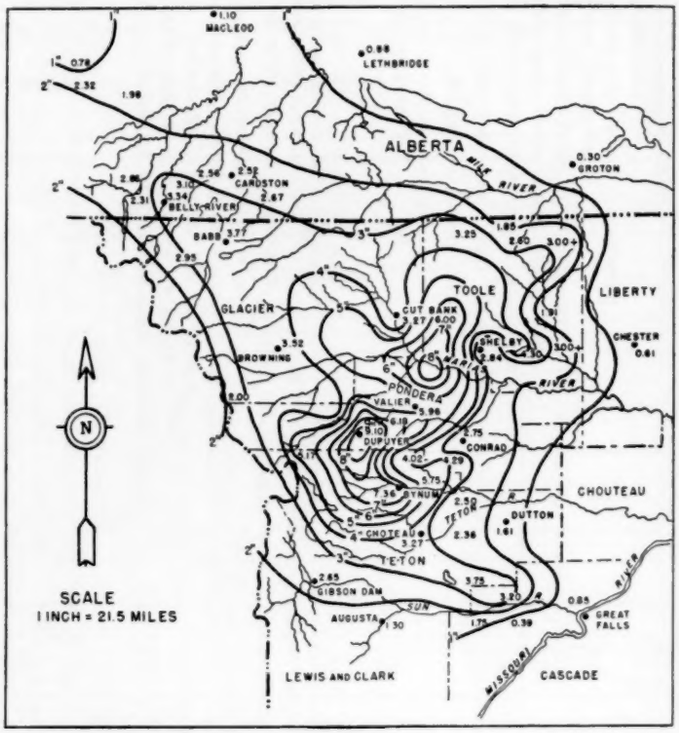

FIGURE 1.—Isohyetal chart for the Marias Basin rainstorm of June 16–17, 1948.

Areas within isohyets from 4 inches to 9 inches were estimated from figure 1 with a planimeter, and depth-area computations were made, following methods outlined by Foster [1]. These computations (table 3) show that the total volume of rainfall within the 4-inch isohyet was 15,248 in. mi.^{2}, or over 35,000 million cubic feet. This enormous quantity of water, coming after more or less continuous rains over the area during the preceding 5 or 6 weeks, resulted in the high discharges and floods discussed in the next section.

TABLE 1.—*Precipitation amounts, June 16–17, 1948*

WEATHER BUREAU COOPERATIVE CLIMATOLOGICAL STATIONS †

	Latitude	Longitude	Elevation (feet)	Precipitation (inches)
	° ′	° ′		
Augusta	47 28	112 23	4,071	1.30
Babb, 6 NE	48 56	113 21	4,461	3.77
Browning	48 34	113 01	4,366	3.52
Chester	48 30	110 57	3,100	.61
Choteau *	47 49	112 10	3,810	3.27
Conrad	48 10	111 58	3,519	2.75
Cut Bank Airport *	48 36	112 22	3,838	3.72
Dunkirk, 16NE	48 39	111 31	3,293	1.91
Dutton, 6 ESE *	47 52	111 35	3,711	1.61
Fairfield	47 37	111 58	3,983	3.75
Gibson Dam	47 36	112 47	4,000	2.65
Pendroy	48 04	112 18	4,264	4.02
Shelby *	48 31	111 51	3,276	2.84
Sherburne Lake	48 50	113 31	4,900	2.95
Summit *	48 19	113 21	5,213	2.07
Sun River, 5 SW	47 28	111 45	3,525	.39
Valier	48 18	112 15	3,800	5.96
RESULTS OF SURVEY OF STORM AREA **				
Bynum	47 59	112 19	3,971	7.36
Bynum, 3 NE	48 00	112 15	‡3,800	5.75
Choteau, 4 NE	47 51	112 07	‡3,700	2.12
Choteau, 6 E	47 49	112 04	‡3,700	2.36
Collins, 9 WSW	47 52	111 59	‡4,600	2.50
Conrad, 10 SW	48 05	112 06	‡4,000	4.29
Cut Bank, 7½ W	48 37	112 31	3,996	4.90
Devon, 6 N	48 33	111 28	3,250	§3.00
Dunkirk	48 29	111 39	‡3,500	4.30
Dunkirk, 9 N	48 35	111 40	3,390	3.10
Dupuyer	48 12	112 30	4,200	9.10
Dupuyer, 8½ NW	48 14	112 35	3,878	5.10
Dutton, 11 E	47 48	111 42	‡3,700	.52
Ethridge, ½ S	48 32	112 07	3,543	7.00+
Ethridge, 4 N			‡3,500	6.00
Ferdig	48 56	111 33		3.00+
Fort Shaw, 3 N	47 30	111 48	‡3,600	3.20
Shelby, 5 W	48 31	112 05		5.00+

See footnotes at end of table.

TABLE 1.—*Precipitation amounts, June 16–17, 1948*—Continued

RESULTS OF SURVEY OF STORM AREA **—Continued

	Latitude	Longitude	Elevation (feet)	Precipitation (inches)
	° ′	°		
Shelby, 5 NW	48 36	111 58	‡3,250	5.75
Simms, 5 W	47 29	111 55	‡3,800	1.75
Sunburst, 8 E	48 53	111 40	‡3,650	2.60
Sweetgrass, 4 SW	48 56	111 59	‡3,800	3.20
Sweetgrass, 7 E	48 59	111 49		1.85
Valier, 5½ W	48 18	112 22	3,897	5.05
Valier, 16 W	48 17	112 35	‡3,800	7.00
Valier, 8 SW	48 13	112 22	‡3,900	8.40
Valier, 5 E	48 19	112 07	‡3,900	5.50
Williams, 7 N	48 23	112 05	‡3,800	8.50
CANADIAN STATIONS †				
Beaver Mines	49 28	114 10	4,218	2.18
Belly River	49 03	113 41	4,550	3.34
Caldwell	49 10	113 28	4,000	2.56
Cardston	49 12	113 18	3,826	2.52
Carway	49 05	113 10	4,000	2.67
Cedar Cabin	49 05	113 52	4,200	2.31
Claresholm	49 54	113 49	3,395	1.42
Groton	49 12	111 20	3,000	.30
Lethbridge	49 38	112 39	3,018	.88
Macleod	49 44	113 24	3,128	1.10
Mountain View	49 09	113 36	4,325	3.10
Pincher Creek	49 28	113 58	3,758	1.98
Waterton Park	49 07	113 54	4,210	2.96

† Measurements made by trained observers using standard equipment. The Canadian data were generously supplied by the Canadian Meteorological Service.

*Hourly amounts are shown in table 2.

** Based largely on surveys of the storm area a few days after storm's end. Evaporation and other losses were not considered; however, amounts considered too doubtful to be useful were not included. Many amounts listed were supplied by persons owning private rain gages. No estimated amounts appear in the table except as noted at Devon, 6 N.

‡ Approximate.

§ Estimated from total for a longer period.

TABLE 2.—*Hourly precipitation amounts (in.)*

Date	Hour ending (MST)																								Daily sum	2-day sum, 5 p. m. 15 June–5 p. m. 17 June
	A. M.												P. M.													
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12		
Cut Bank																										
15																	0.26	0.19	0.01							
16	0.10	0.03	0.01	0.01	0.07	0.06	0.06	0.06		0.05	0.24	0.30	0.18	0.04	0.06	0.11	.07	.10	.07	0.05	0.13	0.25	0.22	0.18	2.45	
17	.19	.13	.08	.05	.16	.03	.02		0.04	.06	.03	.02	.02	.04	.02				.01	.01	.03	.01			.97	3.72
Choteau																										
15	0.10	0.01																0.41				0.34	0.01		.87	
16		.02	0.01	0.01	0.03	0.01			0.01	0.01	0.01	0.04		0.23	0.41	0.26	0.19	.21	0.30	0.23	0.16	.16	.08	0.03	2.41	
17	.02				.01				.01								.03	.01	.01						.09	3.27
Shelby																										
15															0.06	0.11	0.02	0.01							.20	
16										0.06	0.01	0.01			.22	.11	.16	.21	0.17	0.14	0.16	0.16	0.10	0.12	1.63	
17	0.08	0.13	0.23	0.19	0.17	0.23	0.06	0.01		.03	.04	.02	0.01					.01							1.21	2.84
Dutton																										
15																									0	
16																		0.19	0.08	0.03	0.17	0.23	0.03	0.01	.74	
17	0.23	0.25	0.15	0.14	0.06	0.04																			.87	1.61
Summit																										
15											0.03	0.12	0.01	0.04	0.08	0.12				0.04	0.01			0.05	.50	
16	0.06	0.04	0.10	0.20	0.10		0.18	0.02	0.05	0.15	.05	.03	.02		.04	.01	0.05	0.06			.04	0.05	0.15	.06	1.46	
17	.14	.11	.04	.03	.02	0.04	.06	.09				.03	.02							.03					.61	2.07

TABLE 3.—*Depth-area computations for rainstorm, June 16–17, 1948*

Isohyet (inches)	Area enclosed (miles)²	Net area (square miles) between isohyets	Average depth between isohyets (inches)	Rainfall volume		Average depth (inches)
				Increment (in. mi.²) between isohyets	Accumulated (in. mi.²)	
9	46	46	9.05	416	416	9.05
8	128	82	8.5	697	1,113	8.7
7	377	249	7.5	1,867	2,980	7.9
6	770	393	6.5	2,554	5,534	7.2
5	1,575	805	5.5	4,427	9,961	6.3
4	2,750	1,175	4.5	5,287	15,248	5.5

FLOODING AND DAMAGE

The U. S. Geological Survey determined the peak discharge of the Marias River near Shelby, Mont., to be at the rate of 15.4 second feet per square mile, or 40,200 c. f. s. at about 0200 MST, June 18, as compared to the previous peak of 29,500 c. f. s. recorded in 1907. According to the Army Engineer and Geological Survey, flood stages were higher in 1908 several miles east of Shelby downstream, but in the Shelby area, there is no record of the river ever having been as high. Reflecting the fact that most of the storm area was located upstream from Shelby, the peak at Brinkman, downstream from Shelby, was at the rate of about 8 second feet per square mile, or 51,000 c. f. s., slightly less than the peak in the flood of 1908. At many points southwest of Shelby, peak stream flows far exceeded previous high records. Peak discharge rates on some Marias tributaries were very high, exceeding 100 second feet per square mile in some drainages. Some preliminary Geological Survey data for the vicinity of Valier show that Lone Man's Coulee had a peak discharge of 1,820 c. f. s. from an area of 11.4 square miles; Cartwright Coulee, 3,580 c. f. s. from an area of 21.8 square miles; Laughlin Coulee, 820 c. f. s. from an area of 8.4 square miles; and Miller's Coulee, 197 c. f. s. from an area of 1.7 square miles. About 4 miles south of Valier, one 53-acre area produced a peak runoff of 21.6 c. f. s. These drainage areas near Valier total only about 42 square miles, but because they were near the storm center, their discharge rates give some indication of the storm's intensity.

Near Dupuyer, runoff rates were somewhat lower, probably because storm intensity seems to have diminished west of that point. Blacktail Creek, with a drainage area of 63 square miles, had a peak discharge of 4,680 c. f. s., and Dupuyer Creek, draining about 135 square miles, had a peak of 7,800 c. f. s. On the Dry Fork of the Marias River north of Conrad, draining 253 square miles, the peak was determined to be approximately 13,000 c. f. s. These runoff determinations appear to confirm the location of the storm centers in the general areas described in the preceding section.

Stream flows were abnormally high in other areas of the storm, which extended into southern Alberta almost as far north as McLeod. However, flooding in these sections was not quite so severe as around Valier and Dupuyer. The Dominion Water and Power Bureau reported that Lee Creek at Cardston reached the highest discharge in forty years, and at least local flooding was experienced on all streams within the storm's boundaries. Decided peaks were observed by the Geological Survey on both Milk and Sun Rivers (which lie north and south, respectively of the Marias Basin) but serious flood levels were attained only in the Marias (including Teton River) Basin.

Considerable damage was sustained by basement and street flooding in and near the storm's center, severe damage was inflicted to road networks and bridges in Pondera and Teton Counties, and much crop land flood damage resulted in the entire storm area. The U. S. Army Engineers [2] which conducted a thorough survey of damages from this flood, estimated total losses and damage sustained at $1,445,758, in spite of the sparse population and limited development near the river. In all, the Army Engineers estimated that about 28,000 acres of crop land were flooded. No loss of life was reported.

A timely warning issued on the morning of June 17 by the Weather Bureau alerted the river basin from Shelby to the Missouri River confluence at Loma, and Army Engineer, State Police, and Highway personnel were instrumental in aiding persons at Loma and other points to take precautions for safeguarding life and property.

SYNOPTIC FEATURES

The storm which produced the record-breaking rainfall and the severe flooding described in preceding sections had several interesting synoptic features. As is generally the case with unusually heavy rainstorms, a number of rain-producing factors appear to have been involved. The interrelationships among these factors are, of course, complex and the following paragraphs are intended only to point out some of the more important phases.

1. The storm began during the day on June 16 over most of the affected area, generally with thunderstorms. The thunderstorm condition changed gradually to one of moderate to heavy rain. Storm intensity began to decrease early on the 17th, and by late afternoon diminished to light and scattered showers. The surface weather map for 0130 EST June 17 is shown in figure 2. The approximate area of the heavy rain is circled on the chart. The strong High in south-central Canada had maintained itself for several days, drifting gradually southward to the position shown. During the same period pressures fell gradually in northern Wyoming and northern Utah.

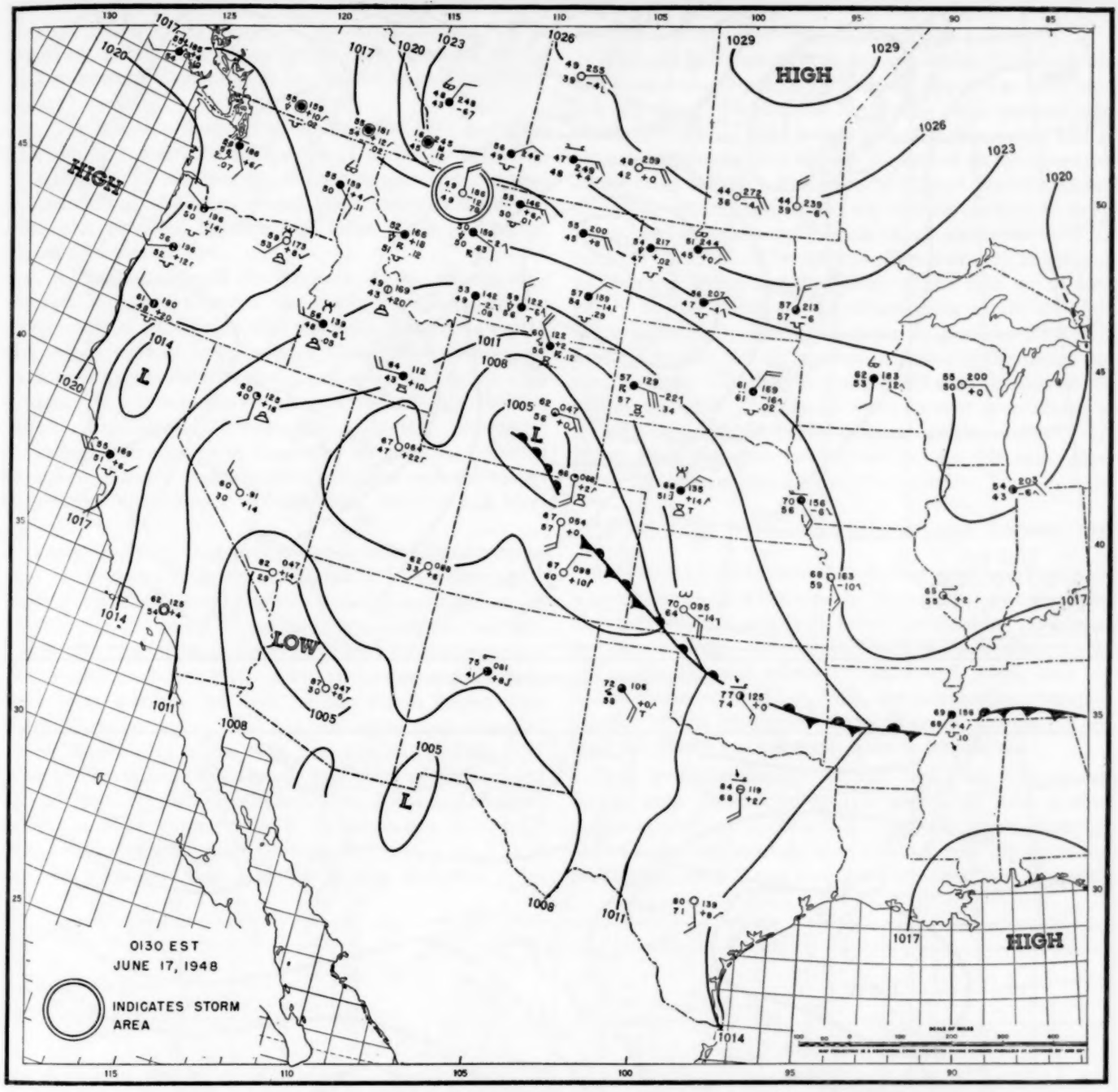

FIGURE 2.—Sea level weather map for 0130 EST, June 17, 1948. The circle in northern Montana indicates the rainstorm area.

The resulting increase in the pressure gradient caused easterly winds of 25 to 30 miles per hour in the lower levels of the atmosphere over western Montana on the 16th and early on the 17th. Figure 3 shows easterly winds near 5,000 feet above sea level, or about 1,000 feet above the surface of the storm area at 2300 EST, June 16, and figure 4 for the same time shows a tendency for easterly winds even at about 10,000 feet above sea level. This broad current from the east was conditionally unstable and relatively very moist (fig. 5). Substantial amounts of rainfall almost invariably occur along the eastern slopes of the Divide in connection with easterly upslope winds.

2. On the 16th, there existed an area of frontogenesis over central Wyoming between the easterly current of cold air to the north, and a very warm and moist southerly current over the Plateau. The 700- and 850-mb. charts for 2300 EST June 16 (figs. 3 and 4) show that the warm

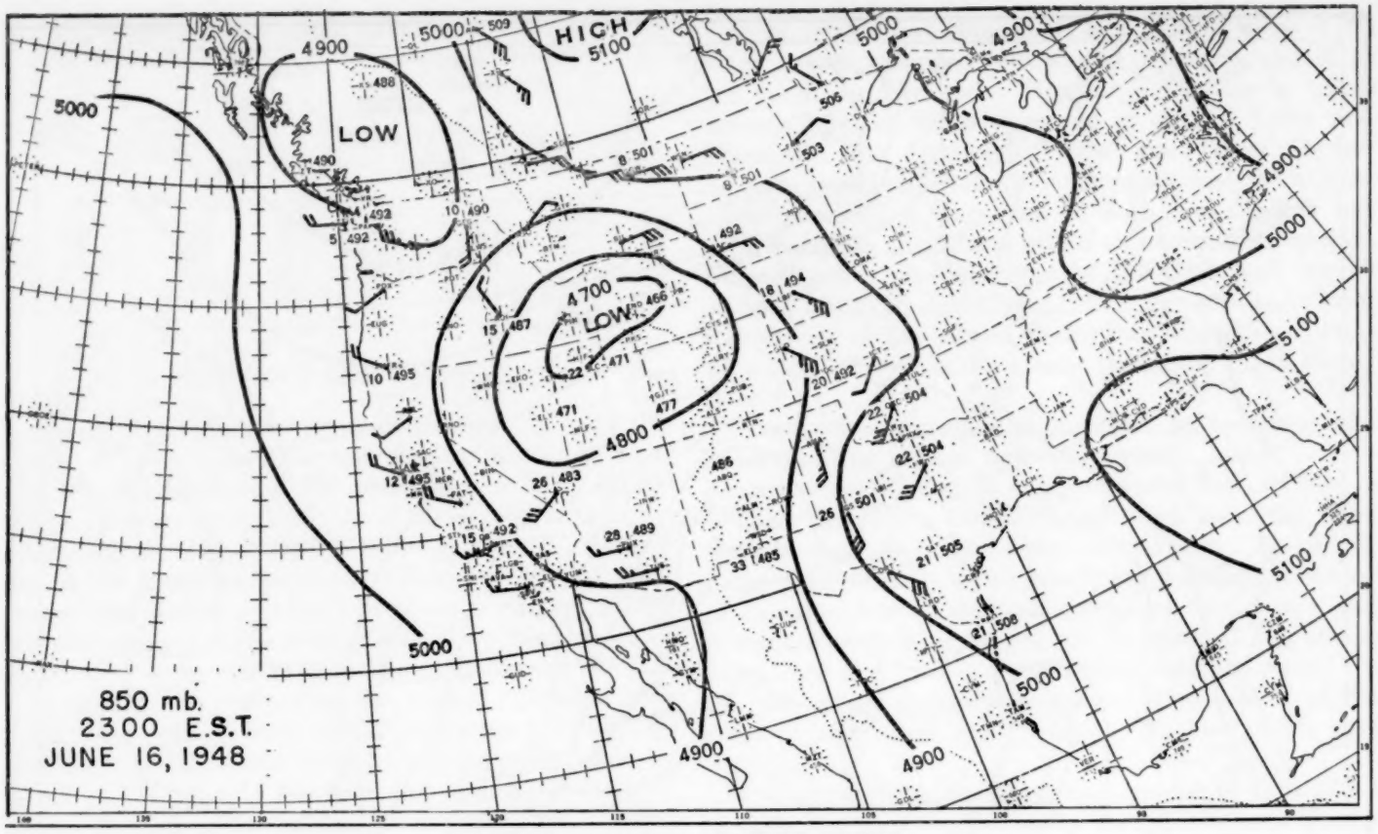

FIGURE 3.—850-mb. chart for 2300 EST, June 16, 1948.

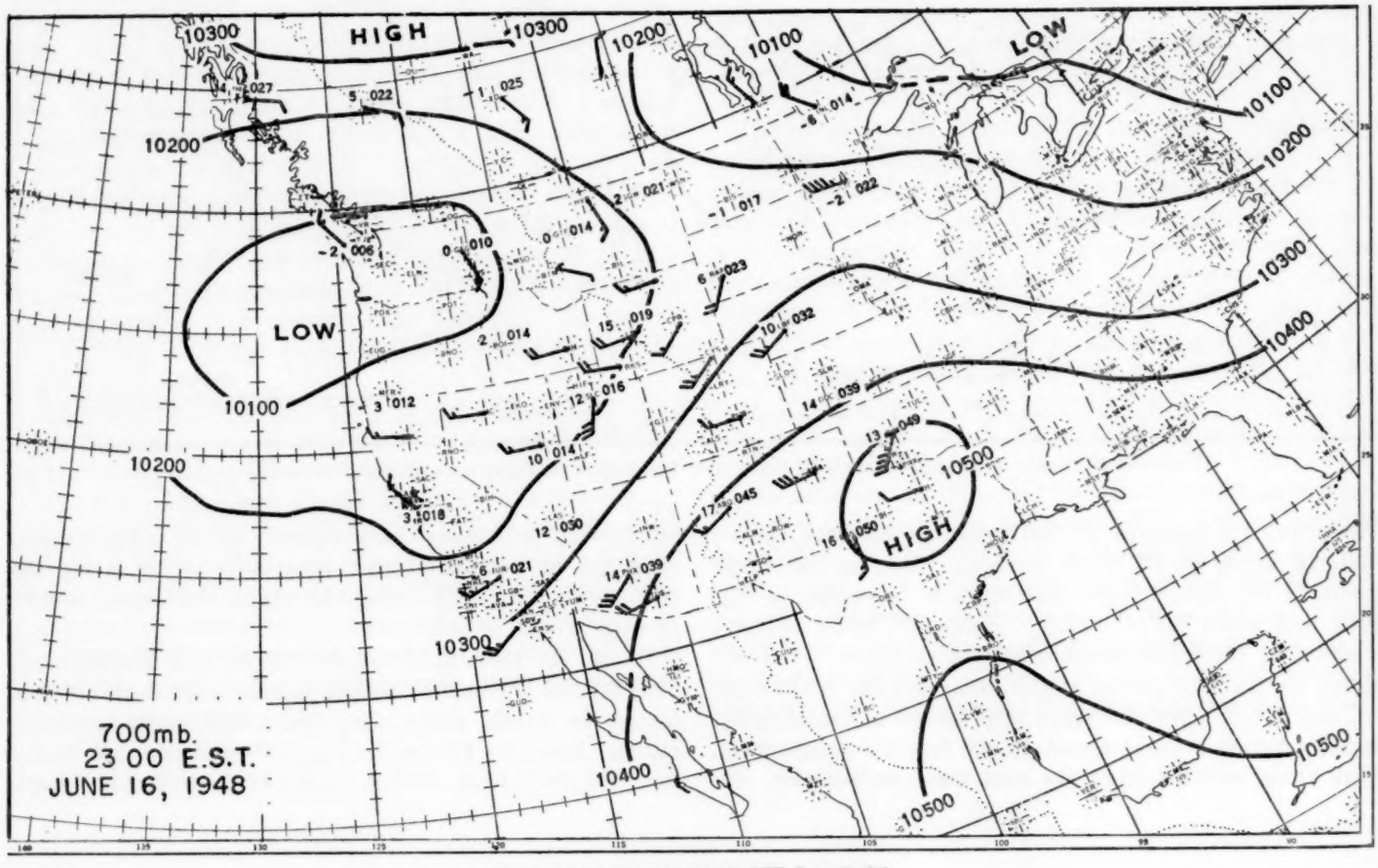

FIGURE 4.—700-mb. chart for 2300 EST, June 16, 1948.

current curved cyclonically aloft as it was forced to rise over the cold easterly current in western Montana. This condition persisted apparently for more than 24 hours, with weakening beginning to be evident on the 1100 EST June 17 charts.

3. The radiosonde observations for 1100 EST and 2300 EST June 16 and 1100 EST June 17 at Great Falls (fig. 5), indicative of conditions in the storm area, showed that conditional instability increased, apparently, as the storm got under way and continued at Great Falls in varying degree for several days.

4. A marked zone of convergence existed over northwestern Montana between the easterly winds near the surface east of the Divide, and the light westerly to southerly winds west of the Divide. The surface convergent pattern is particularly well-defined over the storm area in figure 2. Winds show this convergence also at the 850-mb. (fig. 3) and 700-mb. (fig. 4) levels. Normally, horizontal convergence in the upper air may be expected in regions of sharp cyclonic curvature, and such curvature is apparent throughout the storm at the 700-mb. level (fig. 4).

It appears, then, that four rain-producing factors operated in the areas of heaviest rainfall: (1) The orographic effect of the Continental Divide on the easterly current at lower levels; (2) warm, moist air overrunning the easterly current; (3) conditional instability; and (4) convergence. Both conditional instability and convergence seem likely to have been involved at first, as the storm began with heavy thunderstorms. The heaviest rains were observed during the evening of the 16th, and it is on the 2300 EST June 16 charts that the upslope and convergent patterns appear best developed. Based upon measured rainfall totals, the combined operation of all factors was apparently most intense near Dupuyer, where 9.10 inches fell. It is interesting to note that Dupuyer is only about 25 miles east of the Divide, and that the plain rises rapidly to the summit of the Divide west of that point.

While all four factors were present during the storm, the one most concentrated over the area appears to have been convergence. Conditional instability was general over western Montana both before and after the storm, and its release therefore seems to have depended on the operation of the other factors. The easterly current near the surface of course contributed to the convergent pattern at lower levels, and a good supply of moist air aloft was essential for heavy rainfall. The upslope effect was very important, particularly in adding the lifting of the cold air at least partly to the lifting of the overrunning moist air aloft. With a gradually increasing pressure gradient producing upslope winds, the air masses involved being moist and conditionally unstable, convergence being present at the surface and aloft, and a moist warm current overrunning an already rising moist cooler current at the surface, very heavy rains were the natural result over the area where these factors combined most effectively.

COMPARISON WITH OTHER MONTANA RAINSTORMS

It is interesting to note that during the 40-odd years for which records on a reasonably State-wide basis are available for Montana, nearly all record-establishing rainstorms occurred in June. The Springbrook storm of June 17–21, 1921; the Warrick storm on June 6–8, 1906; and the Evans storm on June 3–7, 1908, are outstanding examples. Studies of the Springbrook and Warrick storms [3] and data for the Evans storm [4] have been published.

From available data, it appears that both Warrick and Springbrook storms covered larger areas with greater precipitation depths than the June 1948 storm, however, both these storm centers were located over 200 miles east of Pondera and Teton Counties, at elevations averaging

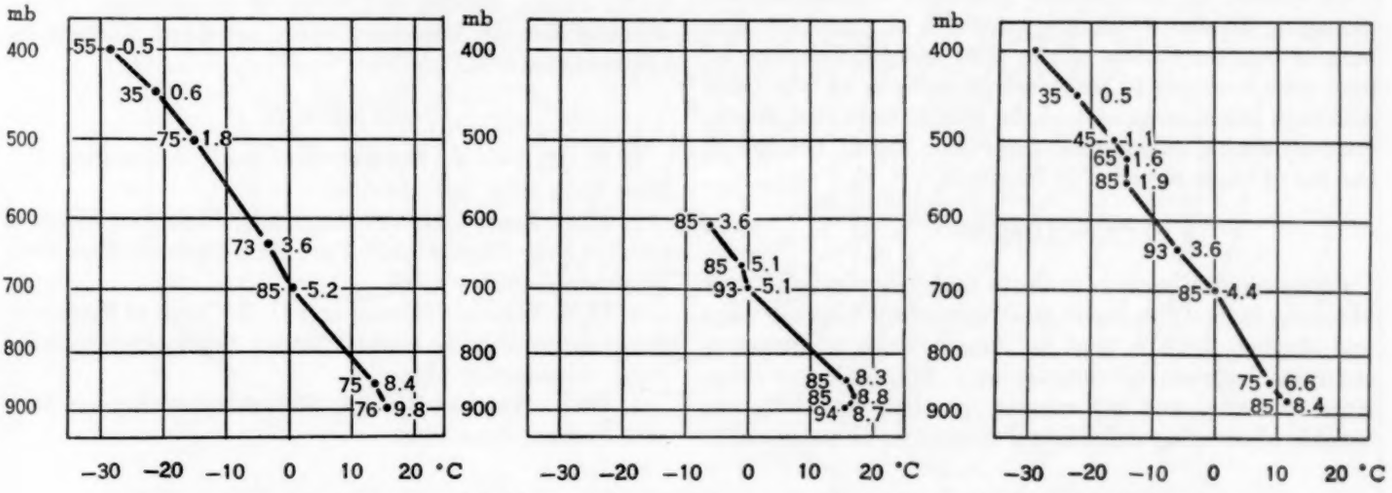

FIGURE 5.—Upper air soundings at Great Falls, Montana. (a) 1100 EST, June 16, 1948; (b) 2300 EST, June 16, 1948; (c) 1100 EST, June 17, 1948.

over 1,000 feet lower. The Evans storm of 1908 covered a much smaller area, although its duration was 5 days as compared to less than 2 for the 1948 Dupuver storm. Precipitation totals and durations at the centers of the four storms are listed:

Storm	Precipitation	
	Total (inches)	Duration (hours)
Warrick, June 6–8, 1906	13.3	54
Evans, June 3–7, 1908	10.1	120
Springbrook, June 17–21, 1921	[1] 15.1	108
Dupuyer, June 16–17, 1948	9.1	36

[1] 10.5 inches in 6 hours.

A detailed comparative study of the four rainstorms is beyond the scope of this article, but it may be worthwhile to point out some interesting similarities as well as distinct differences revealed by an examination of the surface weather maps for the storms. All four storms were associated with unusually slow moving low-pressure centers lying in pressure troughs extending north-northwestward. The low-pressure center in 1948 lay to the south of Montana and deepened very little as it moved slowly eastward. But in the 1906, 1908, and 1921 storms, the low centers moved across Montana and deepened by large amounts. The high-pressure center advancing from the north, which was an important feature of the 1948 maps, was not present on the 1906, 1908, and 1921 maps. As in the 1948 storm, the air to the east of the low-pressure trough in the three earlier storms, warm and moist and apparently of Gulf origin, flowed northward along the eastern slopes of the Continental Divide and overran the cooler air to the north. This cooler surface air, flowing from the east moved upslope north of the cyclonic center. Thus, it seems that the rain-producing factors operating in the 1948 storm had been present in varying degrees also in the 1906, 1908, and 1921 storms.

Of course, all four storms produced widespread and damaging floods. With the exception of slight overlapping of boundary areas of the 1906 and 1921 storms, all four were confined to independent sections of Montana. Although other areas east of the Divide have had heavy, flood-producing rainstorms, these four are at the top of the list of those recorded in Montana.

CONCLUSIONS

Climatological records indicate that heavy rainfall over Montana is likely to occur most frequently between May and August, with a peak in June. Since temperature contrasts between air masses over Montana are often large in June, and air masses, particularly aloft, are capable of carrying much larger quantities of water vapor than during earlier months, slowly moving disturbances in June may be expected to produce heavy rains. During May, even though disturbances, and temperature differences between air masses, may be more marked than in June, only infrequently does water vapor content of the air reach the heavy rainfall-producing quantities possible in June. On the other hand, while water vapor content continues to increase on the average until mid-summer, frontal differences and disturbances become weaker, and later heavy rains appear more likely to be local in character, and to depend chiefly upon convection processes.

Unfortunately, it is not possible to estimate where or when a storm comparable to the one of June 16–17, 1948, will visit Montana again. However, given the right combination of meteorological factors, storms of similar—or even greater—magnitude may be expected in future years. That this combination of storm-producing elements will occur again seems safe to assume; it has happened at least four times in the last 50 years, not counting several lesser but also severe storms during the same period. Such occurrences demonstrate the damaging capacity of rainstorms, and sound long-range development of the area seems to require planning which includes calculation of maximum rainstorm possibilities. Fortunately, studies have been made of many major storms, and long-range development planning is making ever-increasing use of such data.

ACKNOWLEDGMENTS

The author is indebted to the Helena Geological Survey Office for discharge data and much general information, to the Weather Bureau-Air Force-Navy Analysis Center, Washington, D. C., for suggestions on synoptic features, to the Fort Peck Army Engineer for detailed flood data, and to the Canadian Meteorological Service for rainfall data for the storm area in Canada. Mr. L. T. Pierce, Official in Charge of the Billings, Mont., Weather Bureau Forecast Center, provided much of the synoptic material.

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2. U. S. Army Corps of Engineers, *Report on Floods in the Fort Peck District 1948*, Fort Peck District, Fort Peck, Montana, January 1949.

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THE WEATHER AND CIRCULATION OF JANUARY 1950[1]

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One of the most outstanding features of the general circulation of the Northern Hemisphere during January 1950 at the 700-mb. level (and throughout the troposphere) was the strong ridge which extended in a northwest direction from a center of high pressure about halfway between Hawaii and Lower California to the Arctic Ocean (see fig. 1). The maximum positive anomaly of 700-mb. height associated with this ridge, 900 feet in the Alaskan peninsula and southeastern Bering Sea, is by far the greatest anomaly ever observed in this region on any monthly mean map during our 18-year period of record (1932–50), and has been exceeded only once at any place in the entire Northern Hemisphere.[2] At sea level the maximum positive anomaly in this region was 25 millibars, a value which has been exceeded only once (January 1909) during the past 50 years. Although a discussion of the evolution and cause of this tremendous ridge is beyond the scope of this article, its effects upon the general circulation were of the utmost importance for the weather of the United States. In general agreement with the principle of conservation of vorticity, it was accompanied by deep troughs and large areas of negative height anomaly at 700 mb. to both its east and west. Figure 1 shows that

[1] See charts I—XI following p. 21, for analyzed climatological data for month.

[2] A positive 700-mb. height anomaly of 910 feet was observed on the west coast of Greenland during February 1947 (see article by Namias in MONTHLY WEATHER REVIEW, vol. 75, No. 8, August 1947, pp. 145–152).

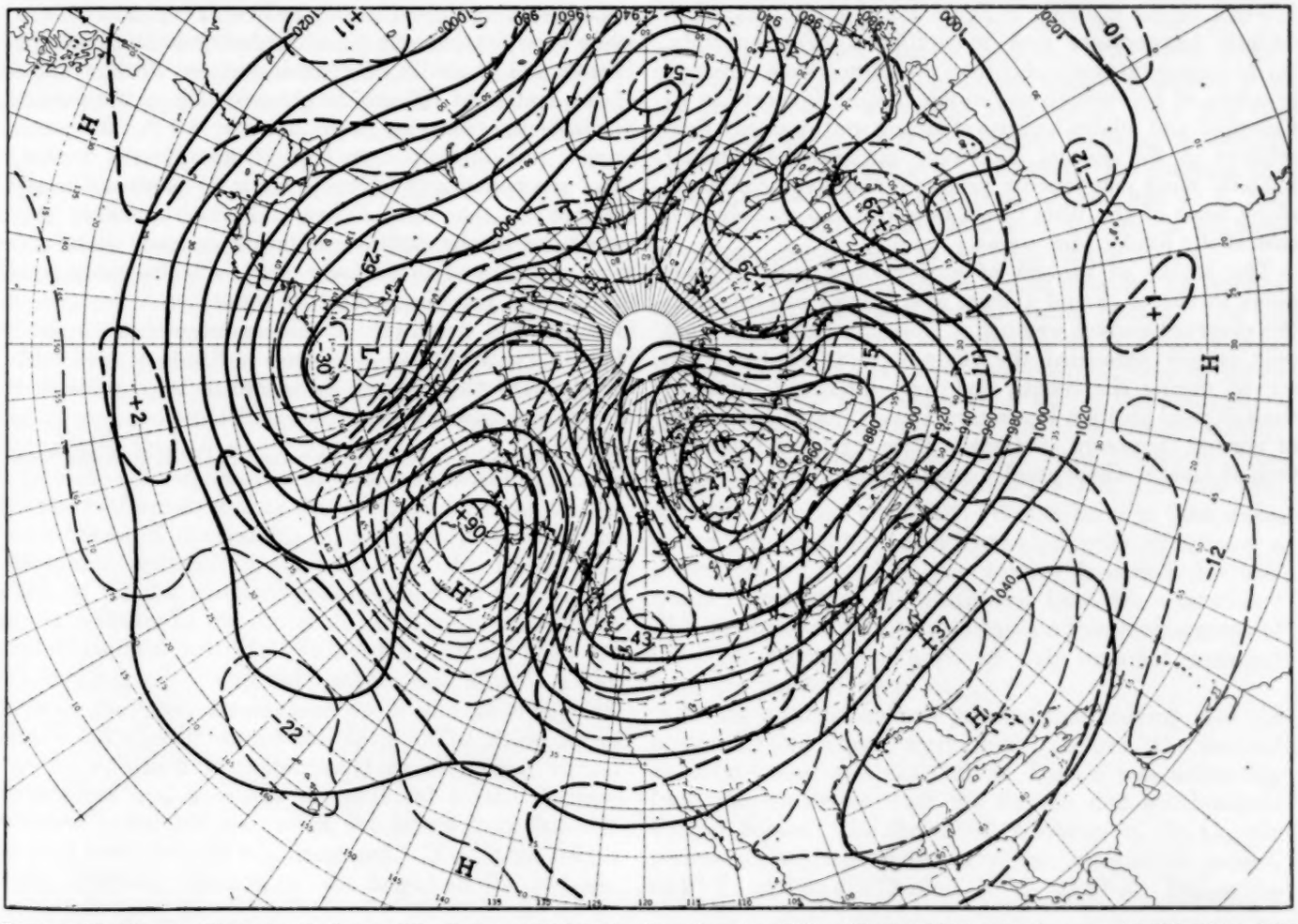

FIGURE 1.—Monthly mean 700-mb. chart for January 1950. Contours at 200-foot intervals are shown by solid lines, 700-mb. height departure from normal at 100-foot intervals by dashed lines with the zero isopleth heavier. Anomaly centers and contours are labeled in 10's of feet. (Chart covers 30-day period Dec. 31, 1949–Jan. 29, 1950 instead of calendar month.)

these circulation features were only a part of a larger system of four roughly sinusoidal waves in the middle latitude zonal westerlies encompassing the entire hemisphere.

This system of planetary waves, with a strong trough and below-normal heights in the West, and an intense ridge and above-normal heights in the East, represents a reversal of the normal January circulation pattern in the United States, which is characterized by a ridge in the West and a trough in the East. Comparison of charts I and V (see inserts following p. 21) with figure 1 shows that, as noted in previous studies of the dependence of weather upon the 700-mb. circulation, the area of subnormal surface temperatures had cyclonic curvature and negative height anomalies aloft, and the region of anticyclonic curvature and above-normal 700-mb. height was characterized by abnormal surface warmth. Similarly, most of the heavy precipitation was located in the region of strong southwesterly flow aloft near the point of inflection between the trough and the next ridge downstream. The departure from normal of the direction of mean air flow is assumed to be parallel to the dashed isopleths of equal 700-mb. height anomaly in figure 1 and is also related to surface temperature and precipitation. For example, surface temperatures higher than the normal were observed in areas of below-normal 700-mb. height in portions of Colorado and Idaho because of strong southwesterly flow relative to the normal. Likewise, stronger-than-normal westerly wind components produced heavy precipitation along most of the West Coast but created a rain-shadow east of the Rocky Mountains.

The tracks of centers of anticyclones and cyclones given in charts II and III are also helpful in explaining the observed surface weather. These tracks for the most part closely paralleled the 700-mb. mean contours observed during the month and were displaced south of their normal position in western United States and north of normal in eastern portions. Thus, cyclones from the Gulf of Alaska, which usually cross western North America just north of the border of the United States, moved generally southeastward along the Alaskan coast through Oregon, Idaho, Wyoming, Nebraska, and Kansas. North of this track the foehn effects were greatly weakened, and intensely cold Arctic air and heavy snows predominated in the Dakotas, Montana, Washington, and Idaho. South of the cyclone track anticyclonic conditions, light precipitation, and milder Pacific air prevailed over most of the Southwest. Both at sea level and aloft the Bermuda High was abnormally dominant over eastern United States. It was instrumental in steering the principal storms northeastward from Kansas through Iowa and Wisconsin to Labrador and in preventing cold polar anticyclones from Alaska from penetrating the country appreciably except in the northern Plains. In fact, the Bermuda High was sufficiently strong to reduce precipitation to light along most of the Atlantic and Gulf Coasts.

The location of the principal 700-mb. troughs and ridges in the entire Northern Hemisphere during January 1950 was similar to that in January 1949.[3] Thus, during both months temperatures were abnormally cold in western Canada and northwestern United States and abnormally warm in eastern United States, the British Isles, and Mexico; while precipitation was generally heavy in the Hawaiian Islands and generally deficient in western Europe. Most of the centers of 700-mb. height anomaly in the western hemisphere, however, were farther north and more intense this January than last. Consequently, westerly wind components (relative to normal) produced wetter weather on the West Coast and much warmer, drier conditions in the Southwest during January 1950 than were experienced in January 1949, when easterly wind components prevailed. On the other hand, the greater intensity and northward displacement of the Bermuda High in January 1950 compared to January 1949 made this January the warmest on record in large portions of the eastern and southern United States.

[3] For detailed discussion of January 1949, see article by Klein in *Monthly Weather Review*, vol. 77, No. 4, April 1949, pp. 99–113.

THE WEATHER OVER THE UNITED STATES ON JANUARY 26, 1950

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The meteorological phenomena in the United States on January 26 have been selected for discussion because they are unusually interesting, and because they were repeated, with little variation, several times during January 1950. The following description, while dealing in detail with the weather of January 26, may be taken to be fairly representative of the trend of events throughout the month. The outstanding features of the weather of January 26 were:

(*a*) The record-breaking high temperatures in the eastern United States;

(*b*) The severe cold in the north-central United States;

(*c*) The heavy rains in the Ohio and lower Mississippi Valleys.

At 1830 GMT January 25 a cold front representing the forward edge of continental arctic air extended from near Detroit, Mich., southwestward to near Ardmore, Okla., thence northwestward as a stationary front through Casper, Wyo. By 1830 GMT, January 26, the cold air boundary was in the position shown in figure 1. The anticyclone centered near Omaha, Nebr., was 18 mb. higher in central pressure than it was 24 hours previously when it was located near Glasgow, Mont. This was the most intense High, as judged by the central pressure, to invade the United States in January. What caused the High to increase in pressure?

The radiosonde observations from Glasgow for 1500 GMT January 25 and Omaha for 1500 GMT January 26 (fig. 2), were chosen to illustrate the internal changes in the High during this period. Figure 3 shows how the height (solid lines) and temperature (dotted lines) at the standard-pressure surfaces as well as the thickness (or mean virtual temperature) of the various layers (dashed lines) of the atmosphere changed in the center of the High. The height of all the standard-pressure surfaces rose as the surface pressure in the center of the High increased; the greatest rise was 2,010 feet at 300 mb. and the least 370 feet at 1,000 mb. The temperature rose sharply at all levels in the lower atmosphere up to and including 300 mb.; it fell slightly above this level. The thickness of each layer, which is proportional to the mean virtual temperature and inversely proportional to the density, increased below 300 mb. while the layers from 300–200 mb. and from 200–100 mb. decreased. If z_0 is the height of the 1,000-mb. surface, z_n the height of the 300-mb. surface, and h the thickness of a layer below 300 mb., these quantities are connected by the relationship [1]:

$$\frac{\delta z_0}{\delta t}=\frac{\delta z_n}{\delta t}-\sum_{i=1}^{n}\frac{\delta h_i}{\delta t}$$

where t is time and δ refers to differentiation following the moving High center. From this equation it appears that the most effective way to build up a surface High (to increase the value of z_0) would be for the 300-mb. surface (z_n), which was near the tropopause on the 25th, to rise markedly while the thickness of each layer of the troposphere becomes much thinner (colder and more dense). However, what occurred in this case was that the 300-mb. surface rose 2,010 feet in 24 hours while the lower atmosphere warmed sharply; the 850-mb. level was 22° C. warmer on the 26th than on the 25th. The entire contribution to the growth of the surface anticyclone came from the stratosphere. It should be borne in mind that the above discussion refers to changes following a moving system, not to changes at a fixed point. For example, the maximum surface temperature at Omaha was 4° F. less on the 26th than on the 25th even though, as we have seen. temperatures rose in the High on the 26th.

The above result is similar to one obtained by Namias [2] in a study of the abnormal winter 1946–47. In his discussion of the higher surface pressure at Thule, Greenland in February 1947 than in December 1946 he states that "it is clear that the lower 6 km. of the atmosphere contributed very strongly (by 15 mb.) toward making February surface pressures lower than December pressures; it is only at approximately 8 km. that the contributions became positive." Wexler [3] says "the warm anticyclone must be caused by the 'piling up' of air over a given region * * * this process is caused by frictional transport of air southward from the westerlies." This mechanism may help to explain the development of the High although the upper air data were not examined from this point of view.

As the anticyclone was growing and moving into the central United States, warm, moist air from the tropical Atlantic Ocean and the Gulf of Mexico was advancing from the southwest over the eastern and southeastern United States. On the 26th, Washington, D. C., experienced its highest January temperature of record, 80.2° F., and so did Canton, N. Y., 63.9° F. Before the

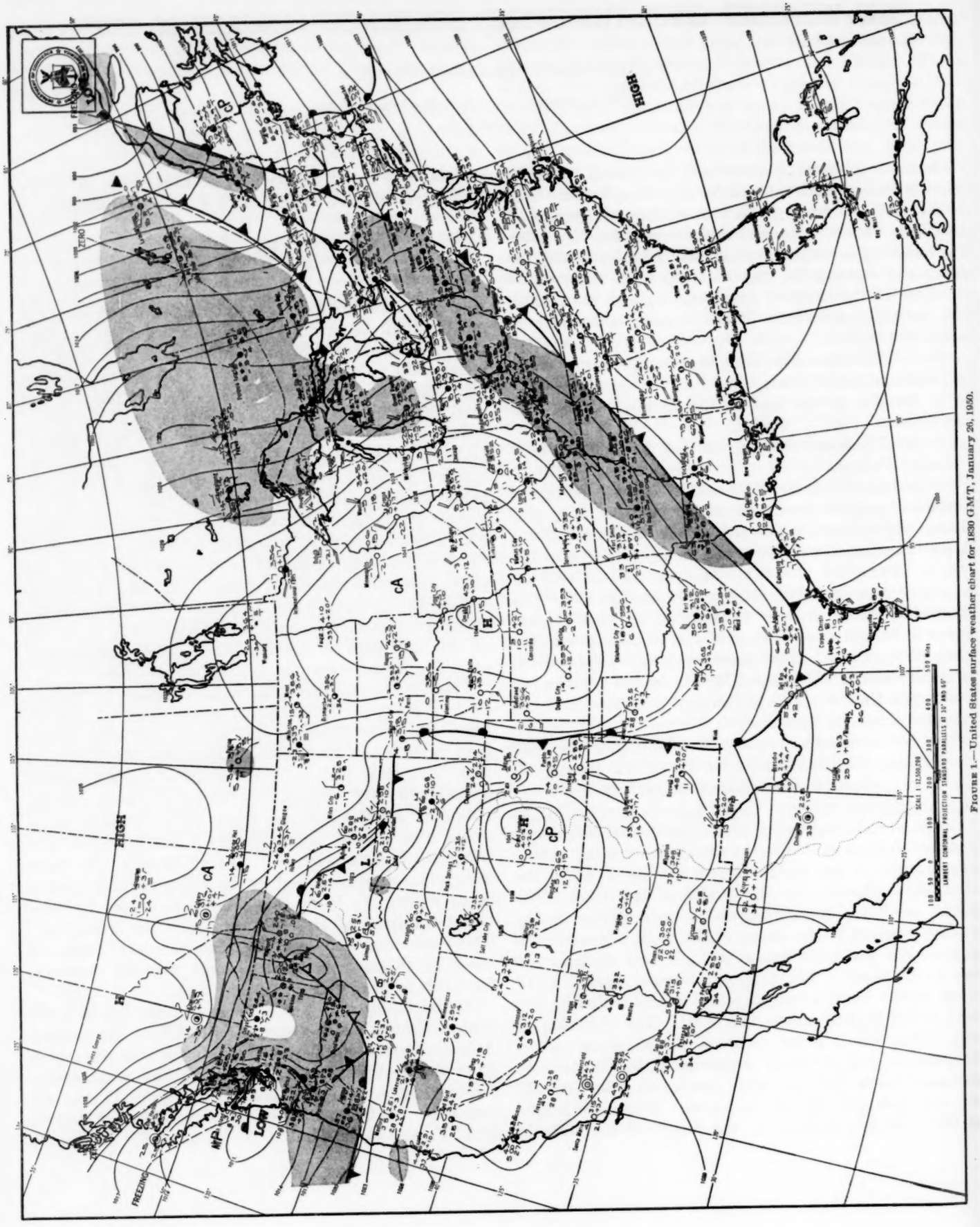

FIGURE 1.—United States surface weather chart for 1830 GMT, January 26, 1950.

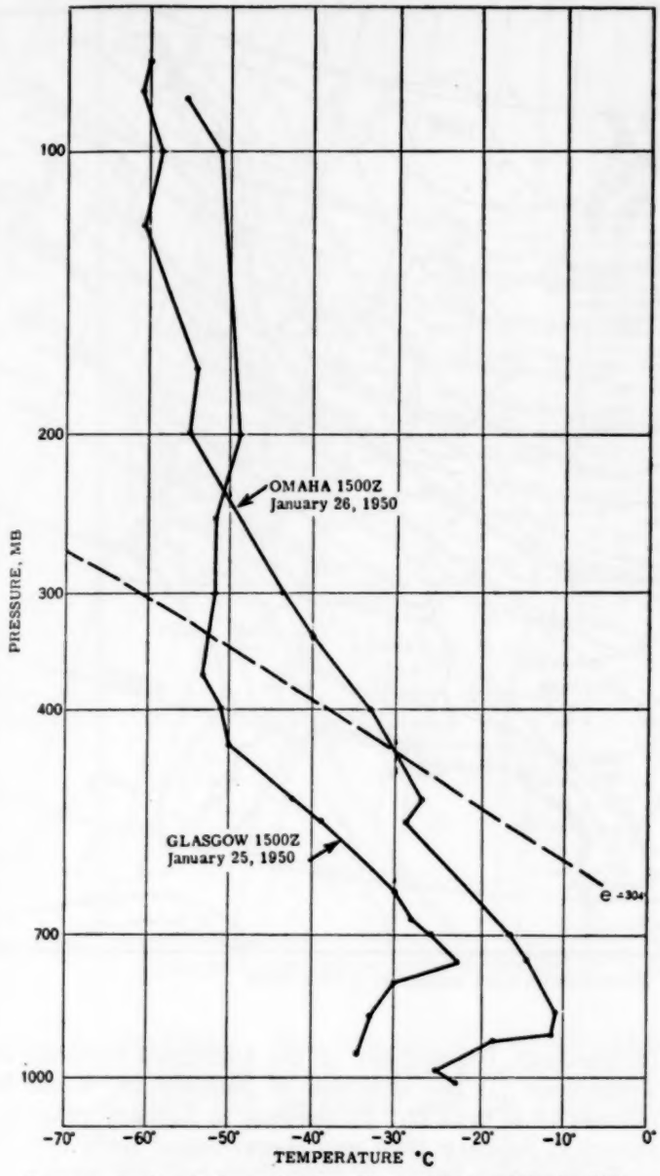

FIGURE 2.—Radiosonde observations from Glasgow, Mont., and Omaha, Nebr.

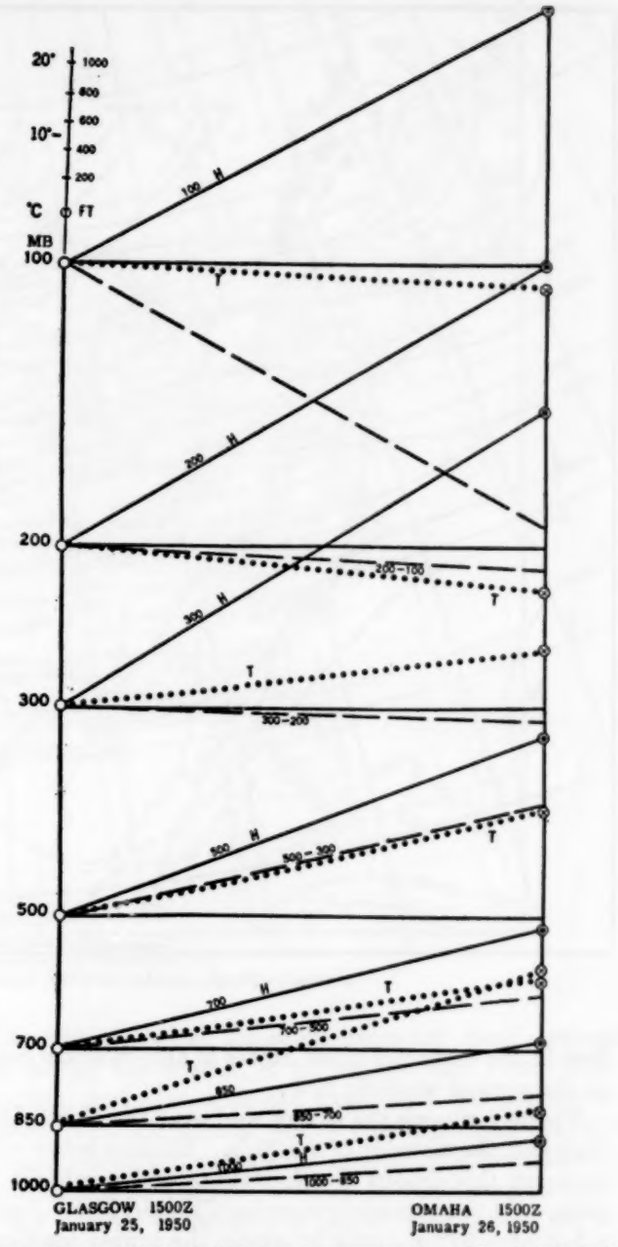

FIGURE 3.—Changes in height (solid lines) and temperature (dotted lines) of standard pressure surfaces, and changes in thickness (dashed lines) of standard pressure layers in the center of the High of January 25 and 26.

cold front passed Columbus, Ohio, during the night of January 25, the temperature soared to 74.0° F. This was not only the highest temperature ever recorded in any January at Columbus, but higher than any temperature ever recorded in December or February there. Remarkable surface temperature contrasts were observed on the 26th. On the morning of that day the lowest temperature at Bismarck, N. Dak., was −38° F. while at Little Rock, Ark., the afternoon temperature reached 75° F., a difference of 113° F. during the same day between points 900 miles apart. The weekly anomalies ranged from +21° F. at Asheville, N. C., to −33° F. at Spokane, Wash., for the period ending January 31, 1950, an unusually great contrast in temperature departures for the same week between different points in the United States [4].

Some idea of the intensity of the warm flow may be obtained by reference to figure 1, which shows the tropical maritime air flowing around the west side of the Bermuda High. Another picture of the warm flow is shown in the 700-mb. chart for 1500 GMT, January 26 (fig. 4). Note first the unusually great height of the 700-mb. surface, 10,600 feet, over the southeastern corner of the country; the normal January height of the 700-mb. surface [5] in this region is about 10,150 feet. The temperature at Atlanta, Ga., is 5.5° C. greater than the January normal [6] and this difference increases northward until it reaches 16° C. at Caribou, Maine. The pronounced southwesterly

877086—50——2

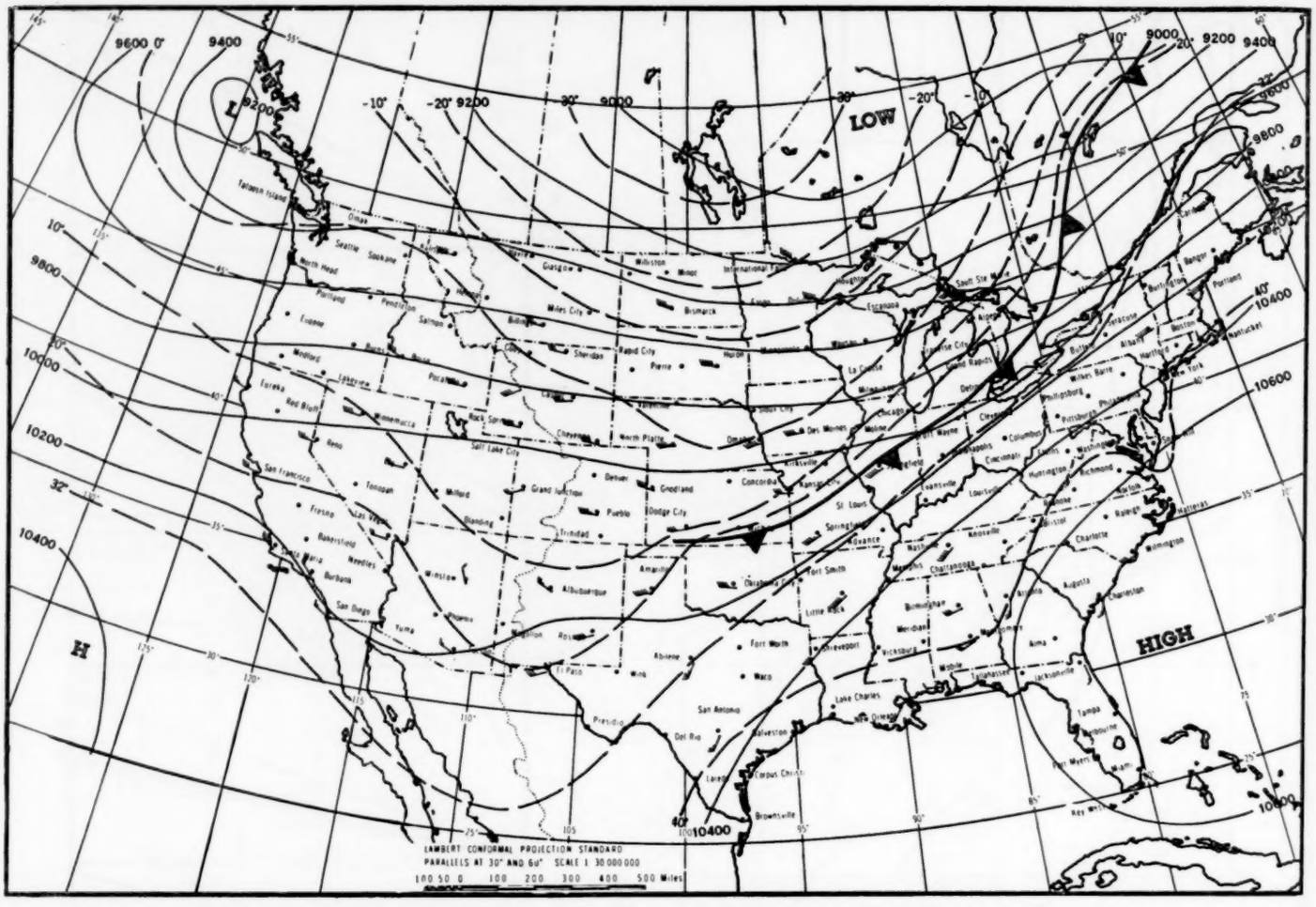

FIGURE 4.—700-mb. chart for 1500 GMT, January 26, 1950. Height is shown in feet, temperature in ° Fahrenheit.

flow in the eastern United States is also in sharp contrast to the normal westerly flow.

Figure 5 reveals the severe cold over the North-Central States on the morning of the 26th. Minima below −30°F. occurred throughout North Dakota and northeast Montana. On the preceding morning Chester, Mont., reported a low of −57° F., only 9° above the lowest temperature ever recorded in the United States. These remarkably low temperatures occurred when the area was under the influence of the increasing High discussed above. Light winds, clear skies, snow cover, and a dry atmosphere favored the loss of large amounts of heat from the surface. The 700-mb. chart (fig. 4) shows that the unusual cold was not restricted to a shallow ground layer. The temperatures in the North Central States were 10° to 15° C. lower than the normal 700-mb. temperatures, and the reason for this is to be found in the northerly trajectory of the air.

Both the surface and 700-mb. charts (figs. 1 and 4) show a Low just off the northwest tip of the State of Washington. This was a persistent feature of these charts throughout the month. In the synoptic-chart classification of the Meteorology Department of the California Institute of Technology [7] the situation of January 26 would be referred to as type D. In contrast to January 1950, the abnormal January 1949 was characterized by a type A pressure pattern [8].

> Type D in winter is characterized by a large crescent-shaped polar High which extends from northwestern Canada west through Alaska, south through the Aleutian Islands and southwest through the Pacific. A major storm develops off the coast of Washington and persists during the period with apparently a new front developing each day. * * * As the two major troughs move eastward across the United States each is followed by a polar outbreak. Rainfall along the west coast is continuous with heavy amounts accumulating [7].

The usual 700-mb. pattern with type D is one with a trough 300 to 500 miles off the west coast of the United States with northwest winds to the rear of the trough and west winds in advance [9]. The reason for the formation of the low pressure area off the west coast of the continent appears to be closely related to the heating of the very cold Arctic air, which comes from northern Asia or the frozen Arctic Sea, by the relatively warm water of the

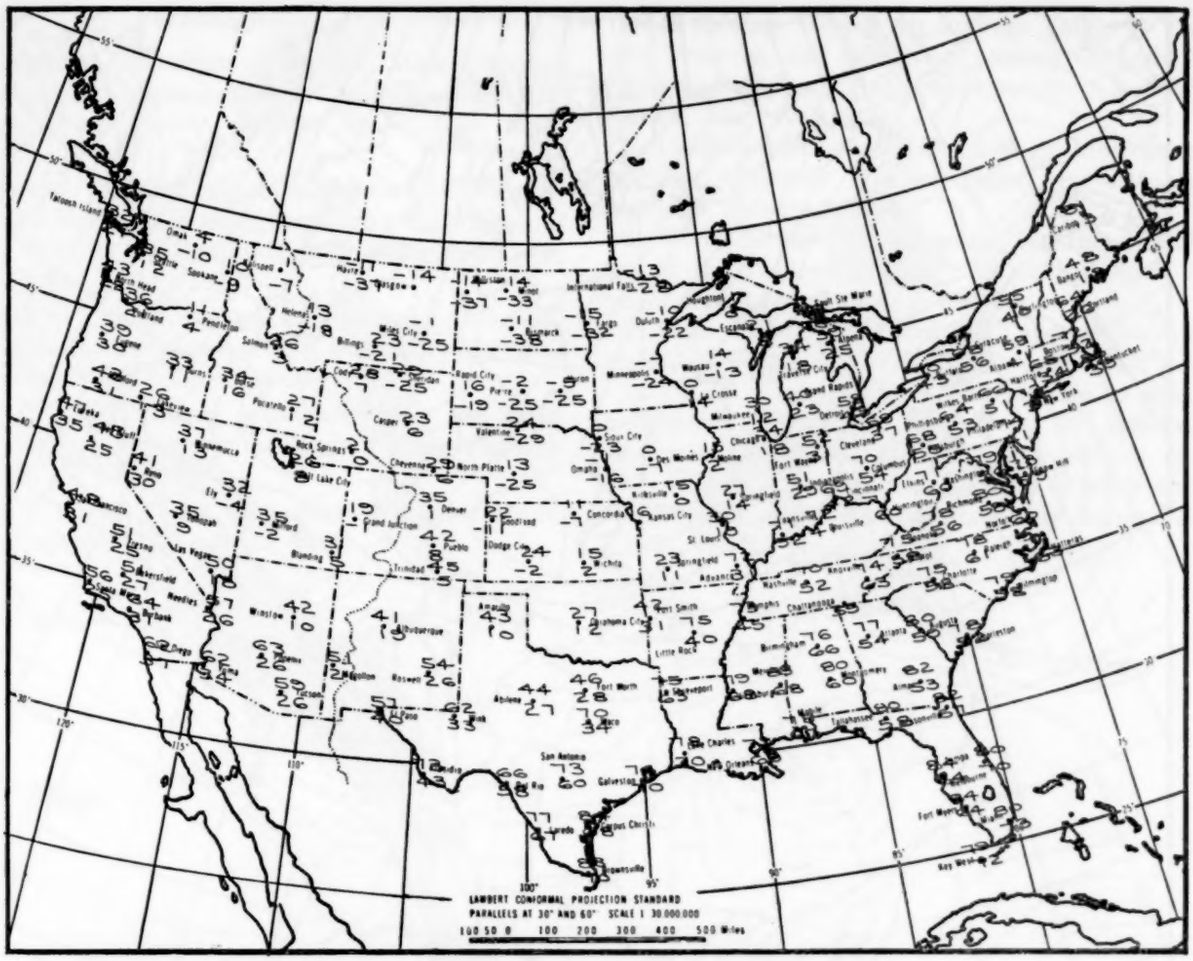

FIGURE 5.—Maximum (top number) and minimum (bottom number) temperatures for January 26, 1950.

North Pacific Ocean. This Low may also be thought of as the eastern lobe of a split Aleutian Low, the western portion of which may be located near the Kamchatka Peninsula.

During the 26th more than an inch of precipitation fell in an oval-shaped area whose longer axis stretched from near Vicksburg, Miss., to Columbus, Ohio, and whose shorter axis ran from near Advance, Mo., to Nashville, Tenn. As the cold front moved eastward that day rain or snow fell all the way from Maine to Texas. The heavy precipitation of the 26th fell just in advance of the 700-mb. trough, in fairly good agreement with the winter precipitation pattern outlined by Klein [10]. The cause of the heavy precipitation was the lifting of the convectively unstable Gulf air (see the Lake Charles sounding for 1500 GMT, January 26 (not reproduced)), from the southwest over the cold northeasterly current at the ground behind the cold front. The instability of the warm air was further revealed in the occurrence of thunderstorms all the way from southeastern Texas to Ohio as the cold front passed these regions.

This meteorological situation repeated itself several times during the month, e. g., on the 6th, 11th, 14th, 16th, 19th, and 31st, with the result that 300 percent to 400 percent of the normal January precipitation [11] fell in a band about 200 miles wide extending approximately from Memphis to Toledo. It may be of interest to compare the weather of January 6 (fig. 6) with that of January 26.

Note that in both cases the Bermuda High is well developed and is bringing a south-to-southwest flow of tropical air over a large part of the eastern United States. The location and intensity of the eastern frontal system, the Plateau High, and the cyclone off the northwest coast of Washington on the 6th agree quite well with the corresponding features of the surface map of the 26th. The chief features of the 700-mb. chart for 1500 GMT, January 26, are found in the 700-mb. chart for 1500 GMT of the 6th (not reproduced). As might be expected, heavy to moderate rains fell in the Ohio and lower Mississippi Valleys on the 6th. Precipitation was heavier on this date in most of Ohio, Pennsylvania, and New York

FIGURE 6.—North American surface weather chart for 1830 GMT, January 6, 1950.

because of the more pronounced cyclonic activity there than on the 26th. A record 24-hour snowfall of 16 inches fell in Spokane, Wash., during the 6th and 7th from the warmer polar Pacific air overrunning shallow, cold continental air. The location of the frontal system and the interaction of the different air masses associated with the persistent off-shore cyclone appear to explain adequately the heavy snowfall.

Temperature extremes also occurred on the 6th; Philadelphia, Pa., reported a maximum of 71° F. that afternoon, while a minimum of 17° F. was reported at Tucson, Ariz., and of 11° F. in the Yuma area.

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U. S. GOVERNMENT PRINTING OFFICE: 1950

Chart I. Departure (°F.) of the Mean Temperature from the Normal, and Wind Roses for Selected Stations, January 1950

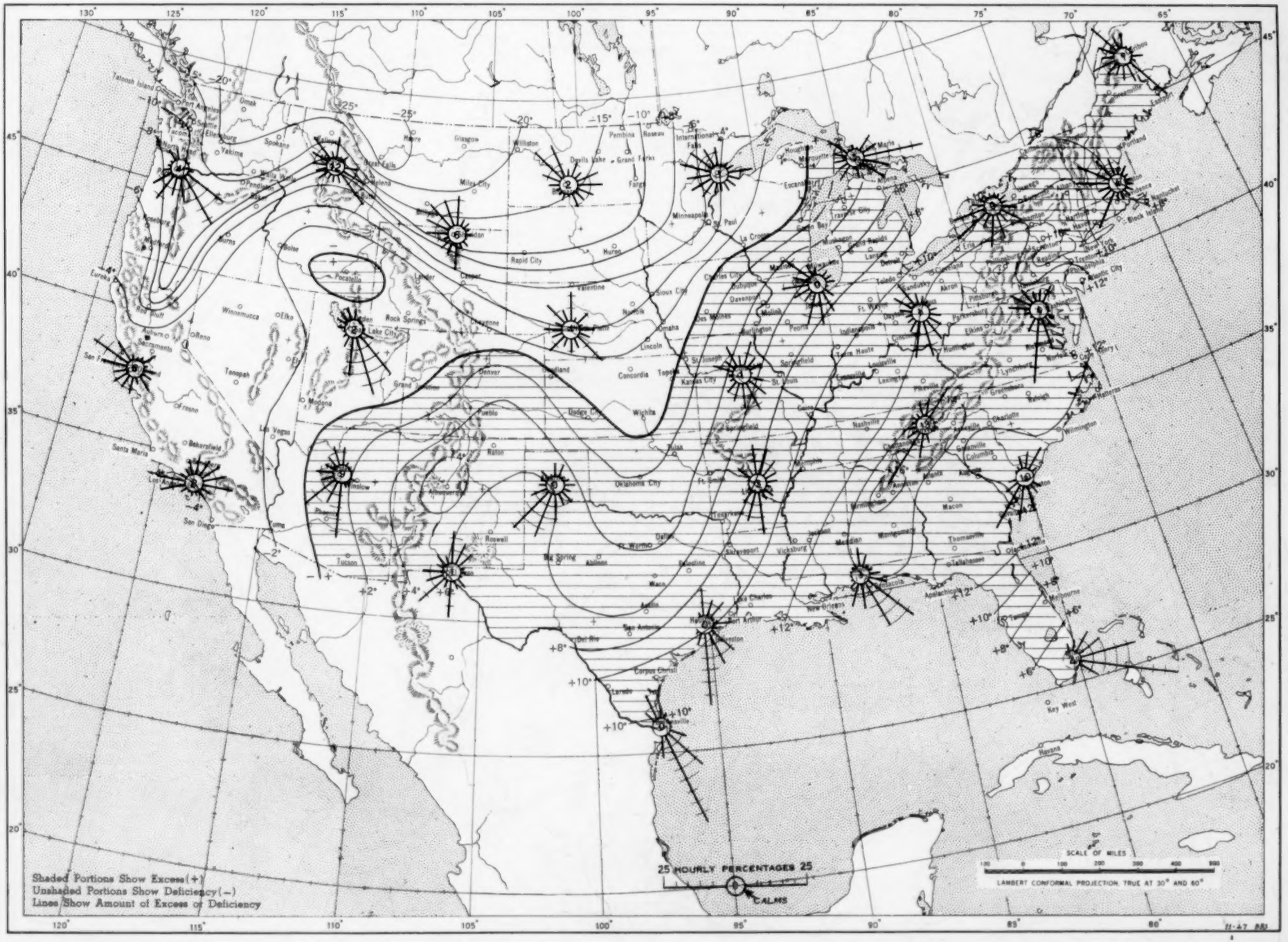
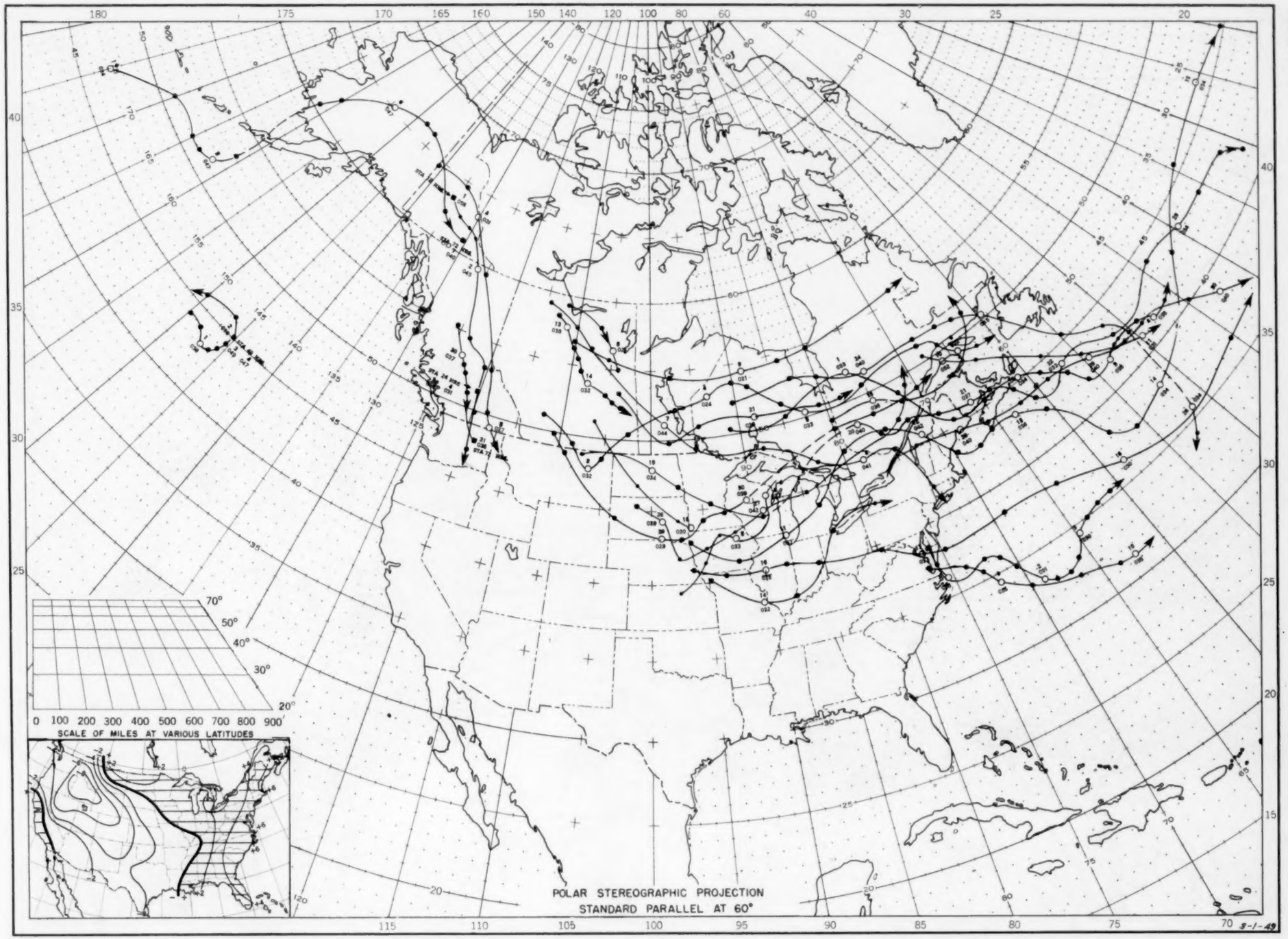
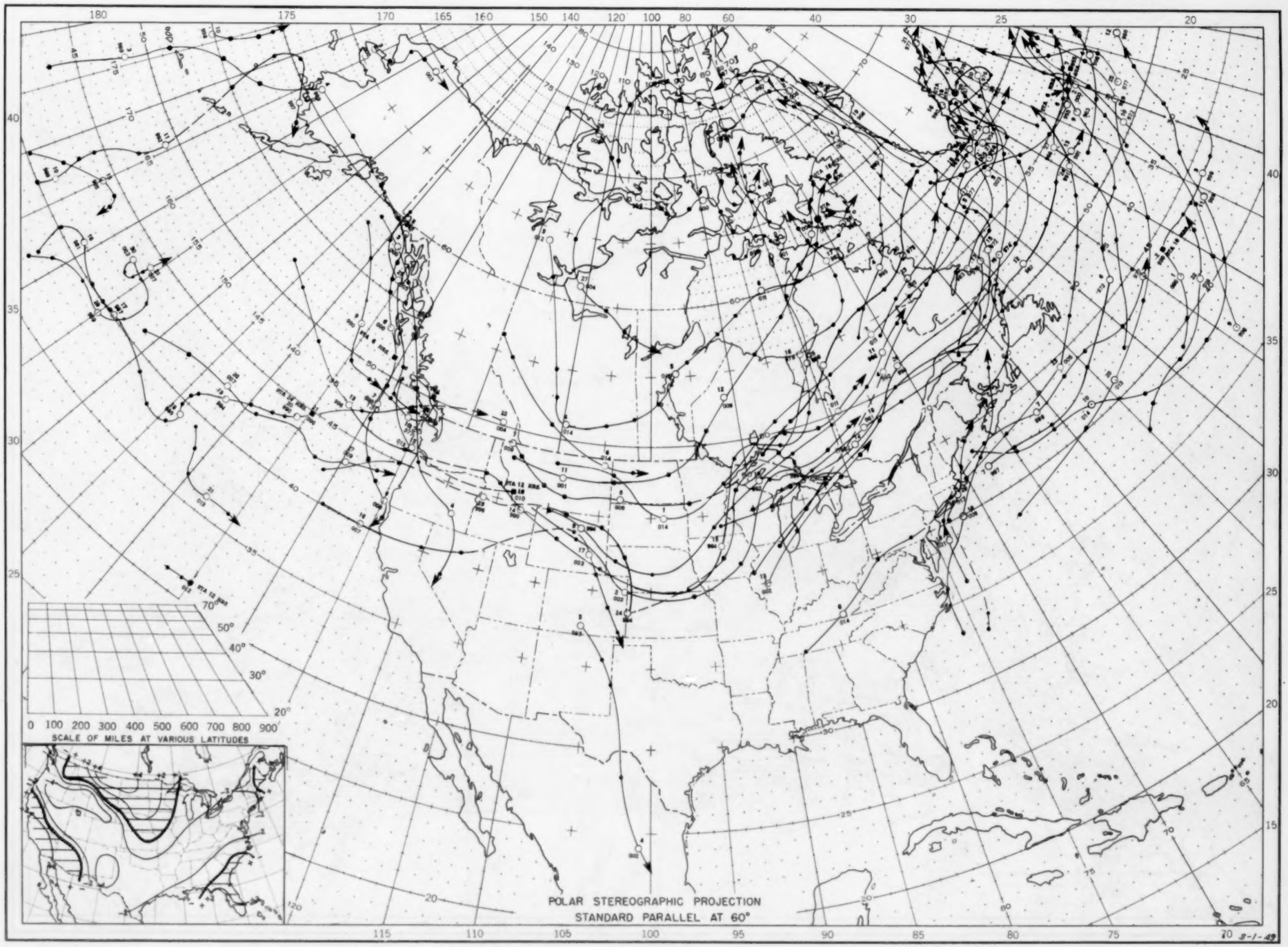

Shaded Portions Show Excess (+)
Unshaded Portions Show Deficiency (−)
Lines Show Amount of Excess or Deficiency
25 HOURLY PERCENTAGES 25
CALMS
SCALE OF MILES
LAMBERT CONFORMAL PROJECTION, TRUE AT 30° AND 60°

Chart II. Tracks of Centers of Anticyclones, January 1950. (Inset) Departure of Monthly Mean Pressure from Normal



Circle indicates position of anticyclone at 7:30 a. m. (75th meridian time). Dots indicate intervening 6-hourly positions. Figure above circle indicates date, and figure below, pressure to nearest millibar. Only those centers which could be identified for 24 hours or more are included.

Chart III. Tracks of Centers of Cyclones, January 1950. (Inset) Change in Mean Pressure from Preceding Month


0 100 200 300 400 500 600 700 800 900
SCALE OF MILES AT VARIOUS LATITUDES
POLAR STEREOGRAPHIC PROJECTION
STANDARD PARALLEL AT 60°
3-1-49

Circle indicates position of cyclone at 7:30 a. m. (75th meridian time) Dots indicate intervening 6-hourly positions. Figure above circle indicates date, and figure below, pressure to nearest millibar. Only those centers which could be identified for 24 hours or more are included.

Chart IV. Percentage of Clear Sky Between Sunrise and Sunset, January 1950

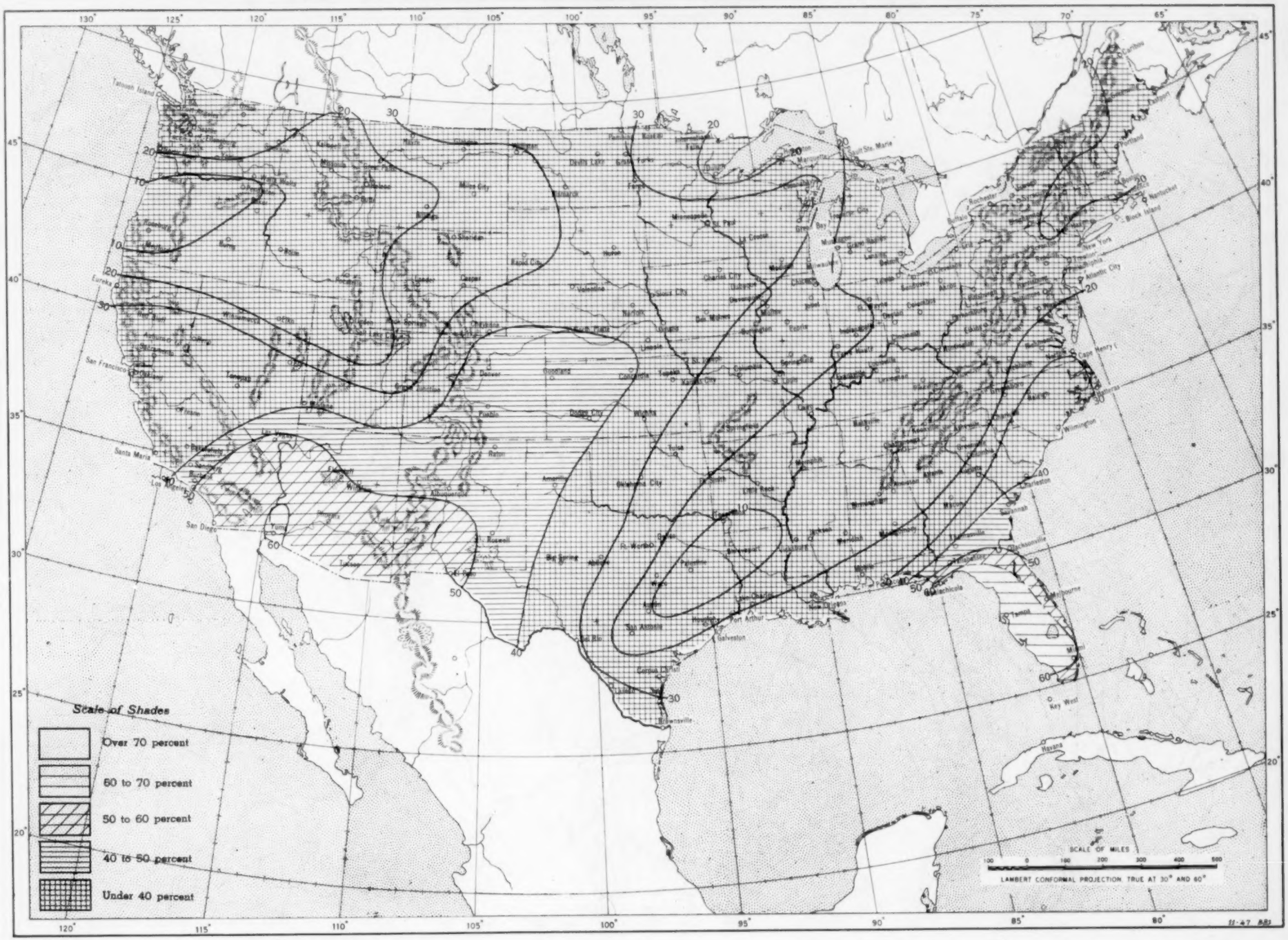

Scale of Shades
Over 70 percent
60 to 70 percent
50 to 60 percent
40 to 50 percent
Under 40 percent
SCALE OF MILES
LAMBERT CONFORMAL PROJECTION TRUE AT 30° AND 60°

Chart V. Total Precipitation, Inches, January 1950. (Inset) Departure of Precipitation from Normal

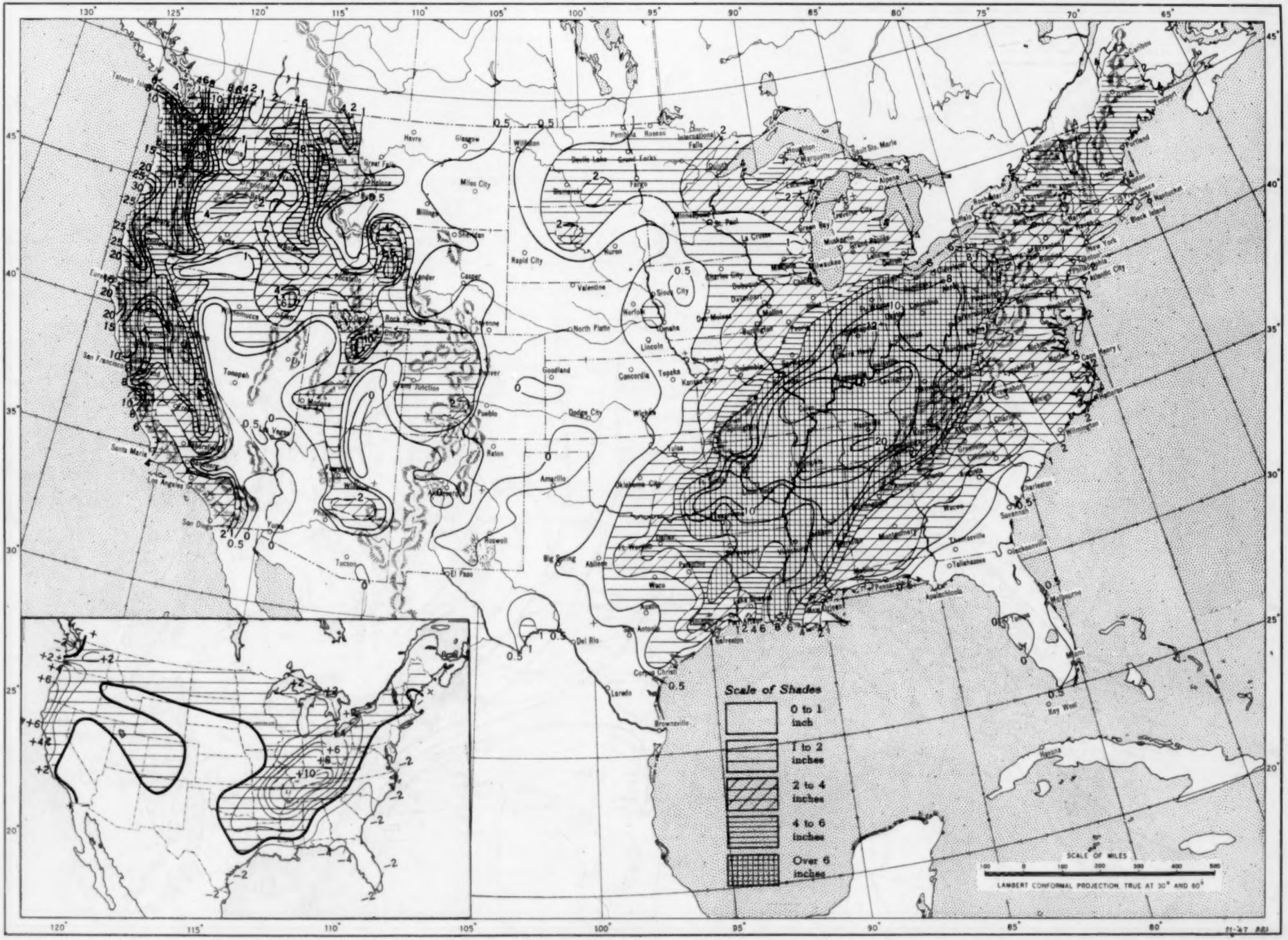

Scale of Shades
0 to 1 inch
1 to 2 inches
2 to 4 inches
4 to 6 inches
Over 6 inches
SCALE OF MILES
LAMBERT CONFORMAL PROJECTION, TRUE AT 30° AND 60°

Chart VI. Mean Isobars (mb.) at Sea Level and Mean Isotherms (°F.) at Surface., January 1950

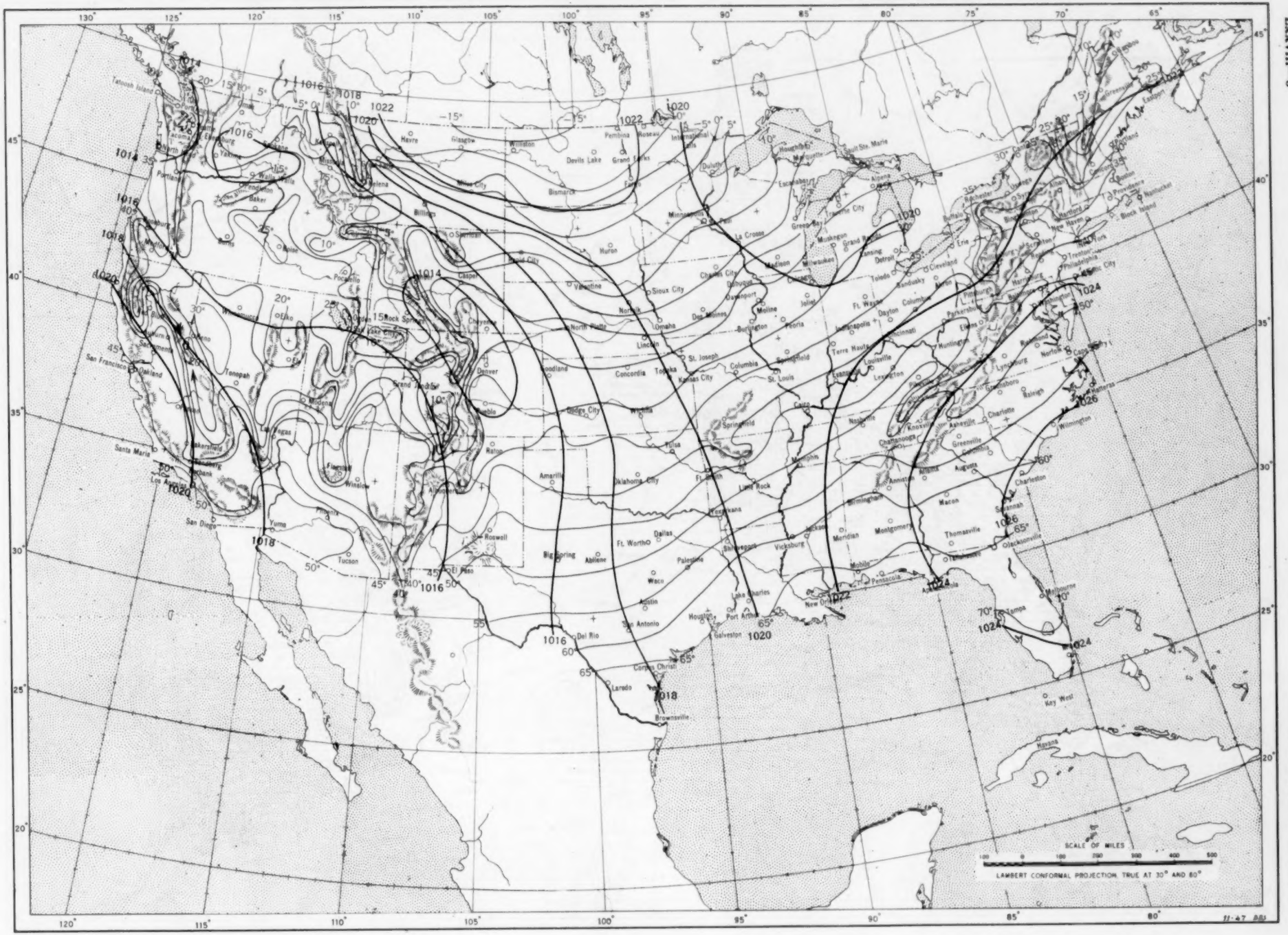
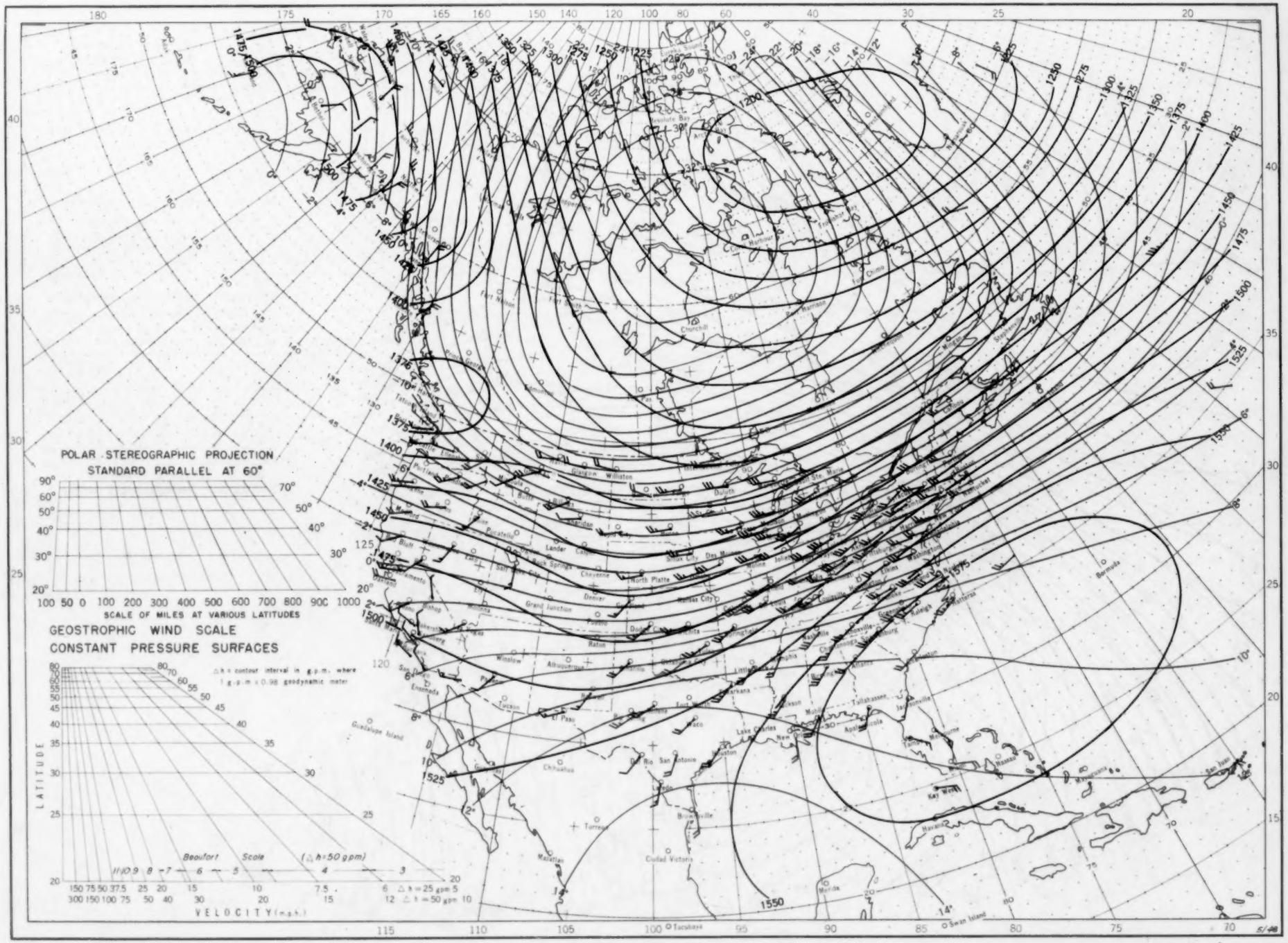


Chart VII. Total Snowfall, Inches, January 1950. (Inset) Depth of Snow on the Ground at 7:30 a. m., January 31, 1950

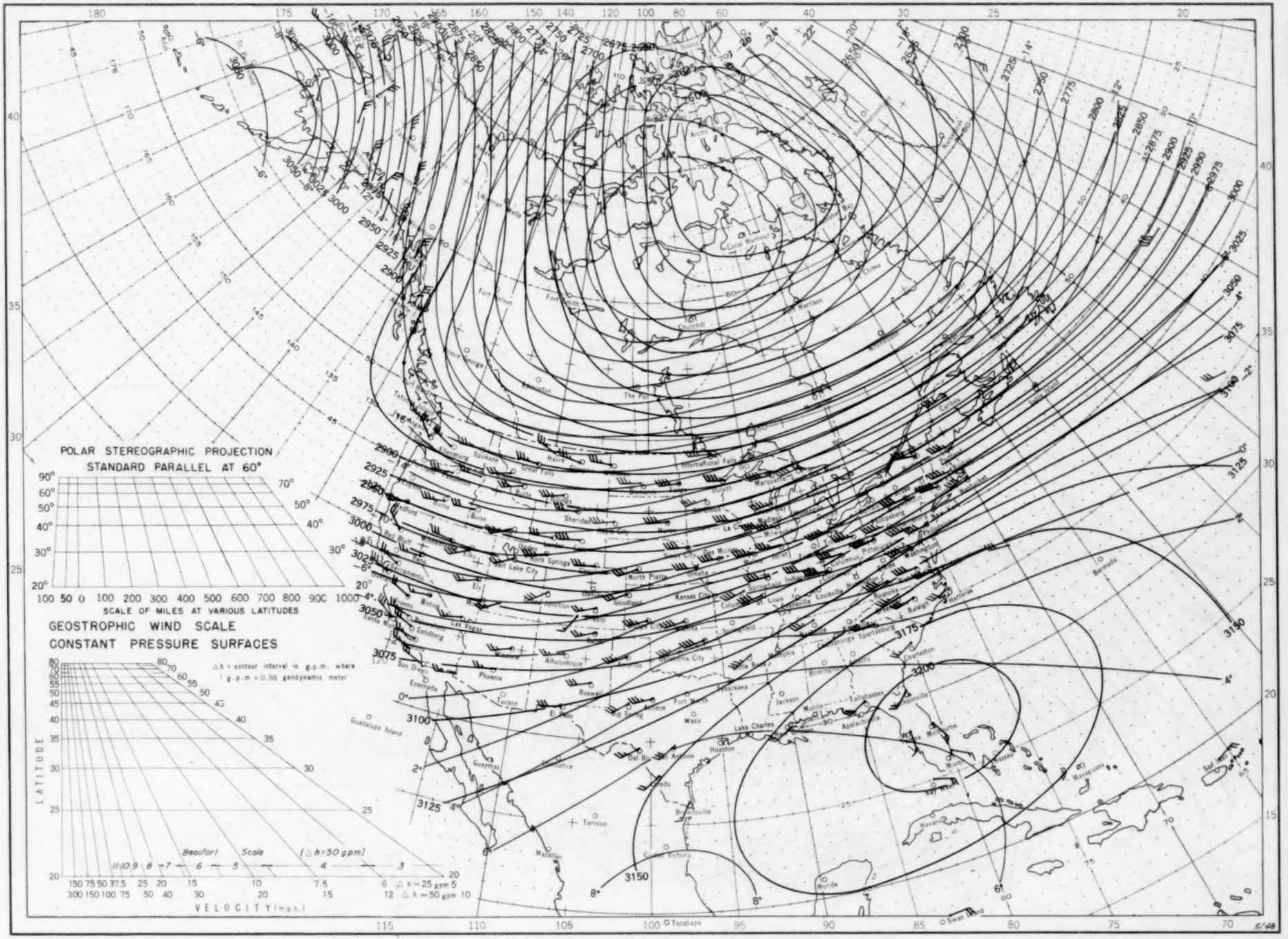
Chart VIII. January 1950 — Contour Lines of Mean Dynamic Height (Geopotential) in Units of 0.98 Dynamic Meters and Mean

Chart VIII, January 1950. Contour Lines of Mean Dynamic Height (Geopotential) in Units of 0.98 Dynamic Meters and Mean Isotherms in Degrees Centigrade for the 850-millibar Pressure Surface, and Resultant Winds at 1,500 Meters (m. s. l.)



Contour lines and isotherms based on radiosonde observations at 0300 G. C. T. Winds indicated by black arrows based on pilot balloon observations at 2100 G. C. T.; those indicated by red arrows based on rawins taken at 0300 G. C. T.

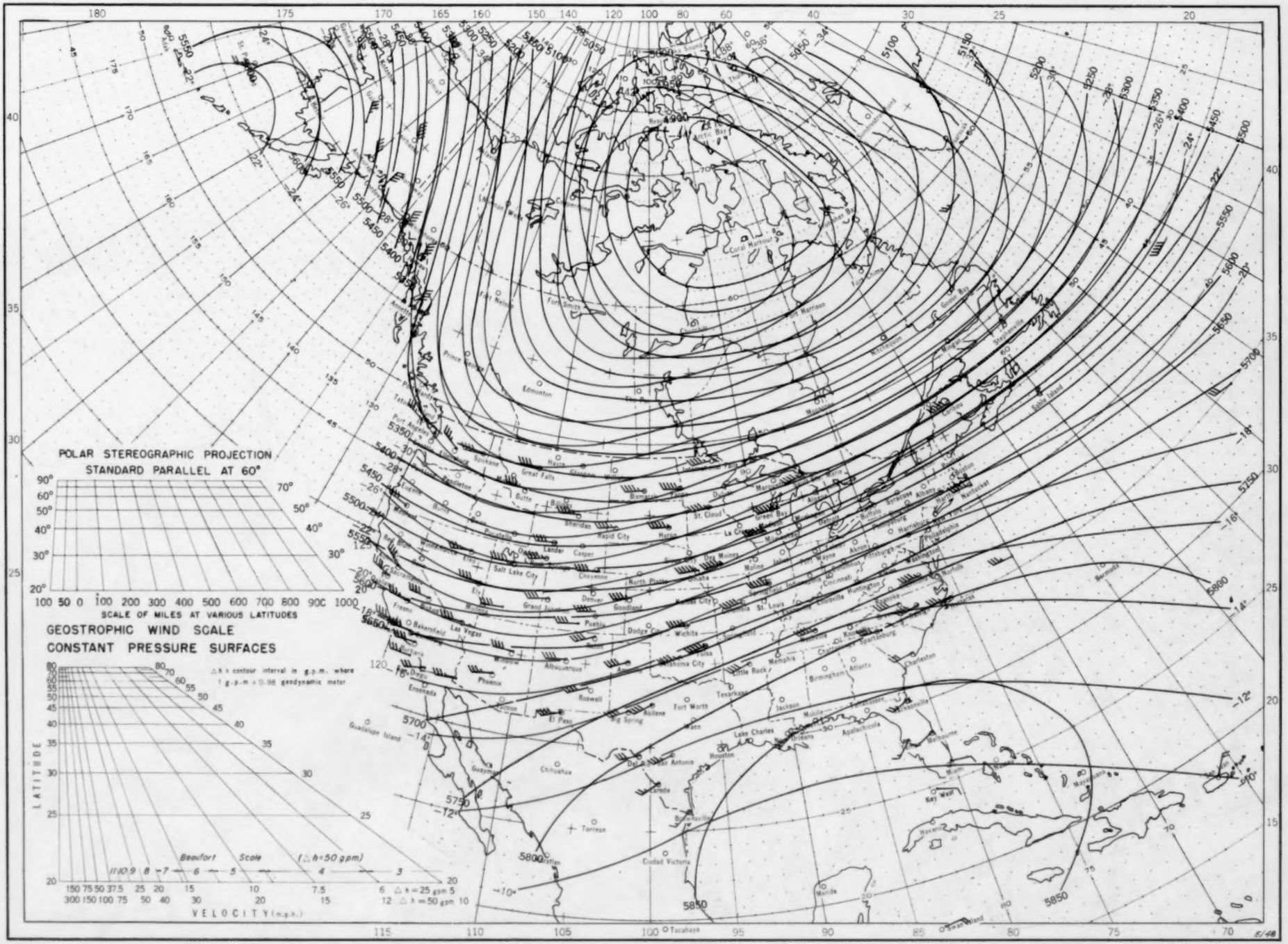
Chart IX, January 1950. Contour Lines of Mean Dynamic Height (Geopotential) in Units of 0.98 Dynamic Meters and Mean Isotherms in Degrees Centigrade for the 700-millibar Pressure Surface, and Resultant Winds at 3,000 Meters (m. s. l.)



Contour lines and isotherms based on radiosonde observations at 0300 G. C. T. Winds indicated by black arrows based on pilot balloon observations at 2100 G. C. T.; those indicated by red arrows based on rawins taken at 0300 G. C. T.

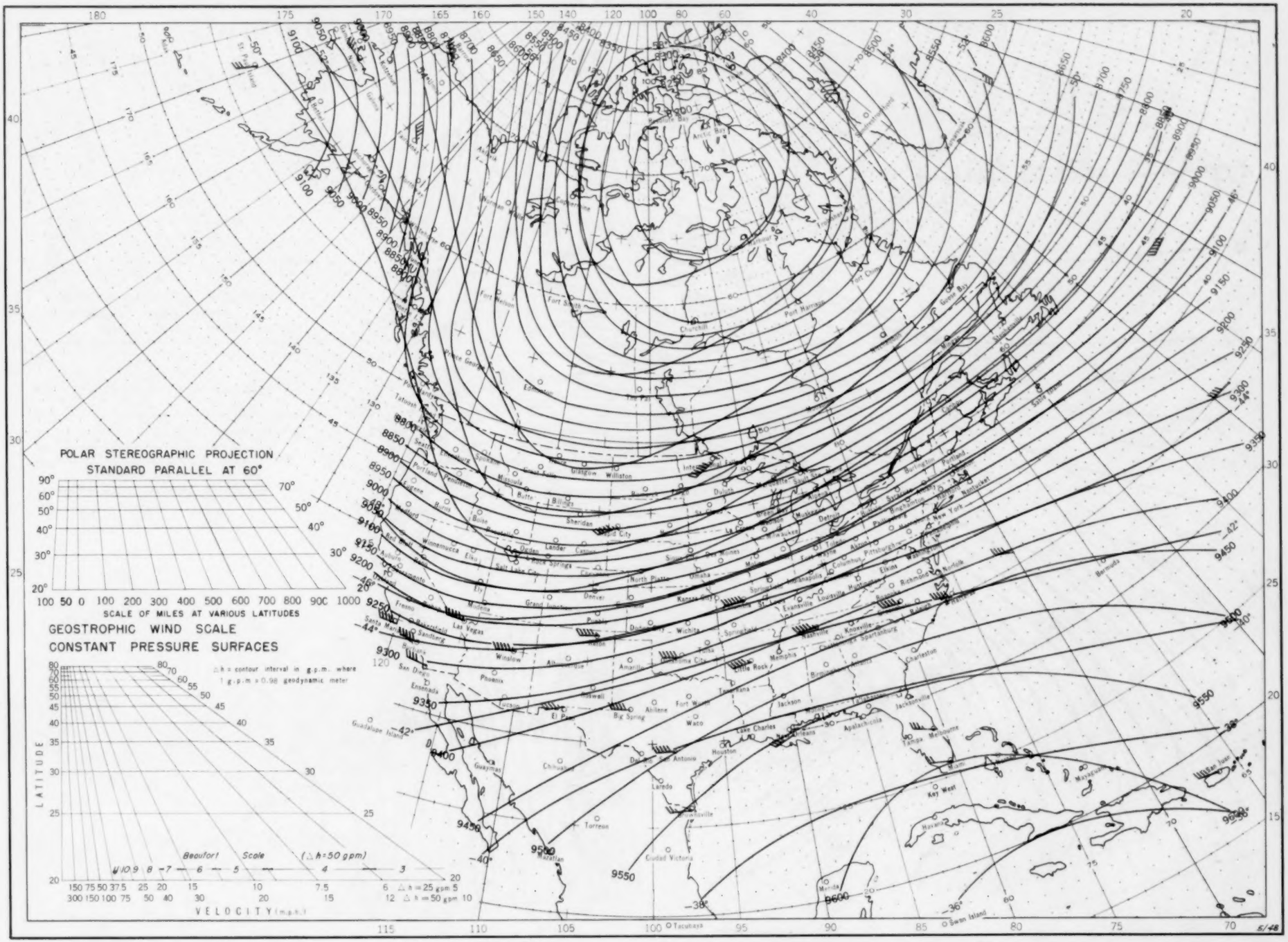
Chart X, January 1950. Contour Lines of Mean Dynamic Height (Geopotential) in Units of 0.98 Dynamic Meters and Mean

Chart X, January 1950. Contour Lines of Mean Dynamic Height (Geopotential) in Units of 0.98 Dynamic Meters and Mean Isotherms in Degrees Centigrade for the 500-millibar Pressure Surface, and Resultant Winds at 5,000 Meters (m. s. l.)



Contour lines and isotherms based on radiosonde observations at 0300 G. C. T. Winds indicated by black arrows based on pilot balloon observations at 2100 G. C. T.; those indicated by red arrows based on rawins taken at 0300 G. C. T.

Chart XI, January 1950. Contour Lines of Mean Dynamic Height (Geopotential) in Units of 0.98 Dynamic Meters and Mean Isotherms in Degrees Centigrade for the 300-millibar Pressure Surface, and Resultant Winds at 10,000 Meters (m. s. l.)



Contour lines and isotherms based on radiosonde observations at 0300 G. C. T. Winds indicated by black arrows based on pilot balloon observations at 2100 G. C. T.; those indicated by red arrows based on rawins taken at 0300 G. C. T.